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EFFECTS OF WEAR METAL ON LUBRICANT DEPOSITION

SOUTHWEST RESEARCH INSTITUTE
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NOVEMBER 1983

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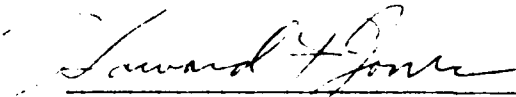
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NOTICE

This technical report has been reviewed and is approved for publication.

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The effects of wear metal on deposit forming characteristics of turbine engine lubricants were investigated, employing hot-wall deposition test rigs. The hot-wall section of the rigs was redesigned, fabricated and assembled for testing. A recently designed wear-metal generator (showing relatively good repeatability and demonstrating good results on a companion program) was employed. Eight MIL-L-7808 or MIL-L-7808-type lubricants were evaluated under five different test conditions. Then a brief statistical analysis was

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20. ABSTRACT (CONT'D)

> performed to determine the micronic filtration tests to be performed in a mitigation of wear-metal effects phase of the effort. Also, the effects on both kinematic viscosity and neutralization number of the test lubricants were determined and are presented. A direct calculation of wear-metal generation was provided by weight-loss measurements of the wear coupons mounted below the lubricant level in the sump. Also, the concentration of wear metals in samples of the test lubricants taken during testing was determined by atomic absorption spectrophotometer. The energy dispersive X-ray fluorescence technique was employed to determine trace elements in hot-wall deposit scrapings.

The preliminary statistical analysis for all eight lubricants consisted of a one-way analysis of variance, then an analysis of covariance using an adjustment for wear, and finally an unadjusted analysis of variance whereby the means of each test parameter were compared among themselves. This latter analysis showed that all wear materials and lubricant types had a significant influence on the mean deposit ratings. Also, there was a significant interaction among lubricants and wear materials. The analysis of variance results using viscosity increase and neutralization number change showed a significant effect between lubricant types, but wear materials were not significant. Based on these results, test conditions employing five of the eight lubricants were selected for the mitigation of effects phase of the program.

The mitigation of wear-metal effects phase of the program consisted of tests having two levels of filtration, namely, 15 µm and 3 µm. Only a limited number of these tests were performed, and based on these results a statistical evaluation showed the deposit rating means were higher when no filtration is present as compared to either 15 µm or 3 µm filtration. The viscosity increase averages for 3 µm filtration were lower than for either 15 µm or no filtration. No filtration differences were apparent when analyzing neutralization number change means. Breakdown of at least two of the lubricants during testing may have influenced the viscosity increase and neutralization number change, thus biasing the effects of filtration results.

FOREWORD

This report was prepared at Southwest Research Institute (SwRI) under Contract F33615-81-C-2021, Project No. 3048. The work was monitored by the Lubrication Branch, Fuels and Lubrication Division, Air Force Aero Propulsion Laboratory, Wright-Patterson Air Force Base, Ohio. The project engineer was Mr. L.J. DeBrohun, AFWAL/POSL.

The report covers the period September 1, 1981 through September 1, 1983.

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SECTION I

INTRODUCTION

Objective and Scope

As specified in the Description/Specifications of Contract F33615-81-C-2021, the objective of the proposed program was to determine the effects of representative engine wear-metal types on the deposit forming tendencies of selected turbine engine lubricants. Also, preliminary exploration of means to mitigate accelerated deposit formation which results from wr metals was to be conducted.

Toward accomplishing these objectives, five major phases outlined in the scope of the Description/Specifications and are as foll. ⌐:

Phase I - Evaluate candidate tests and select a suitable test apparatus capable of accurately and inexpensively measuring the deposit forming characteristics of synthetic turbine engine lubricants. The test apparatus selected must be capable of incorporating a controlled and to the extent possible, repeatable wear-metal generator within the test lubricant system.

Phase II - Identify and select representative metals/alloys to be utilized as test wear coupons.

Phase III - Test a maximum of eight (8) lubricants furnished by the Air Force Wright Aeronautical Laboratories (AFWAL). Data both without wear and with wear employing metals/alloys selected in Phase II will be provided.

Phase IV - Perform limited exploratory testing to achieve some mitigation effects for those lubricant/wear metal combinations exhibiting a significant deleterious effect on deposition. Consider micronic filtration within the lubricant system and/or use of metal deactivator additives in the lubricant to achieve this goal.

<u>Phase V</u> - Analyze and interpret all the test results generated in Phases III and IV above.

Based on a companion program[1]*, a suitable test apparatus and evaluation had already been selected, meeting the Phase 1 criteria. Therefore, this phase was primarily devoted to fabrication and assembly of two newly designed test rigs which will be discussed in Section II and Section IV of this report. Discussions with major engine manufacturers, identified the representative oil-wetted wear metals likely to be found in a turbine engine. From this information representative metals for wear coupon fabrication were selected and will be discussed in Section III of this report. Eight test lubricants supplied by the AFWAL, and described in Section IV, were tested both with and without filtration in accordance with the scope of the program. Finally, analysis, evaluation and interpretation of the data generated during testing were performed and are presented in Section V. Hot-wall summary data for all of the reported tests are presented in the Appendix of the report.

Background

The United States Air Force (USAF) submitted a good resume of background information pertaining to their interest and the state of wear-metal deposition in the Description/Specifications section of Contract F33615-81-C-2921.[2] This overview of the situation certainly seems worthy of further documentation and is included here for added information.

The acceptability of current aircraft turbine engine lubricants is dependent on numerous performance properties, one of which is deposition tendency. Over the years this deposition tendency of specification-approved lubricants, as a class, has been reduced. Nevertheless, because of its pervasive effects on engine operation and maintenance, deposition tendency

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* Superscript numbers in parenthesis refer to the References included in this report.

remains a lubricant characteristic of primary concern. The formation of deposits can hinder the operation of bearings and seals, plug lubricant jets and filters, impede the operation of lubricant coolers and pumps, and affect the performance of numerous other engine components. Aside from the prime consideration of possible in-flight malfunction, engine cleanliness also significantly affects time and cost requirements of maintenance. Furthermore, engine deposits persist even though significant bulk lubricant increases in viscosity or acidity are rarely observed in the field. This is attributed to the fact that deposits occur predominantly in areas receiving indirect lubrication; i.e., areas of thin lubricant films. Thus, discrete portions of the fluid may undergo extreme deterioration, which is not reflected by the condition of the bulk lubricants. Studies have shown a definite interaction between lubricant degradation products and test system wear metal in the formation of deposits. Laboratory tests using fully formulated lubricants indicated a marked deleterious effect on deposits for induced iron metal wear. Thin-film experiments with uninhibited diester and polyolester lubricant base stocks showed that for certain conditions of thermal and oxidative deterioration, corrosive and/or abrasive wear was a factor in the deposition process. Spectrometric analysis of deposit samples of a carbonaceous appearance taken from various locations from test-stand engine (J57) tests revealed metal contents, principally iron, as high as 3.8 wt percent (38,000 ppm). This evidence indicates a chemical combination between nascent wear particles and lubricant degradation products, resulting in acceleration/intensification of system deposits. All of these findings point to the need for a basic examination of the role of wear metal in the deposition process. With such information it may be possible to obviate the reactivity of metal wear particles, e.g., by suitable additives, and thereby substantially reduce the deposition tendency of ester-base lubricants in general. To date, there has been no concerted effort to identify the metals or alloys, typical of engine metallurgies, which may exert significant effects on lubricant deposition. As a consequence, no information exists which could suggest an approach for mitigation of the wear-metal/deposition mechanism.

In a project review meeting prior to initiation of the mitigation of wear metal effects on deposition, it was decided to investigate the effects

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of micronic filtration only, and not pursue the effects of lubricant additives such as metal deactivators. The rationale for this decision was based on the fact that all of the candidate lubricants had been previously formulated and might or might not contain the additives of interest in the recommended concentration. It was thought that additional effort in cooperation with the lubricant formulators would be necessary to plan a viable testing program. Since this was beyond the planned scope of this program, only mitigation of effects by micronic filtration was pursued.

SECTION II

FABRICATION OF HOT-WALL SECTION OF TEST RIGS

General

As already mentioned in the introduction, a companion program having similar experimental tools, i.e., a lubricant deposition test incorporating an integral wear-metal generator, was undertaken approximately one year previous. Therefore, Phase I (Test Selection) of this program, whereby a survey of available test devices or conceivable approaches was to be conducted, was considered already accomplished. As a consequence, Phase I of this program was modified such that the goal of the task was to fabricate and assemble two hot-wall deposition test rigs.

Hot-Wall Section

Details of the basic hot-wall deposition test rig may be found in previously issued technical reports.[3,4] Two of these rigs were being employed on the companion program at the time the contract for this program was issued. Since the configuration for these rigs utilized a No. 2 rear bearing support from a J57 turbine engine, and this item was no longer readily available to Government contractors, it was necessary to redesign and fabricate the hot-wall section accordingly. Also, it was hypothesized that the hot-wall deposition test in its present state of development could be considered for inclusion in the MIL-L-7808 lubricant specification, thus, creating a need for drawings of the component. Therefore, complete and detailed design drawings were developed and two hot-wall sections were fabricated according to specifications shown in Figure 1. As determined by Air Force personnel, it was decided that the original material was AISI 4340 (AMS 6415) steel. Therefore, the deposit surface (test specimen) of the current design was fabricated from the same material. Shown in Figure 2 are details of the spray chamber that mate with the deposit surface. Further discussion of details and operation pertaining to these components are presented in Section IV of this report.
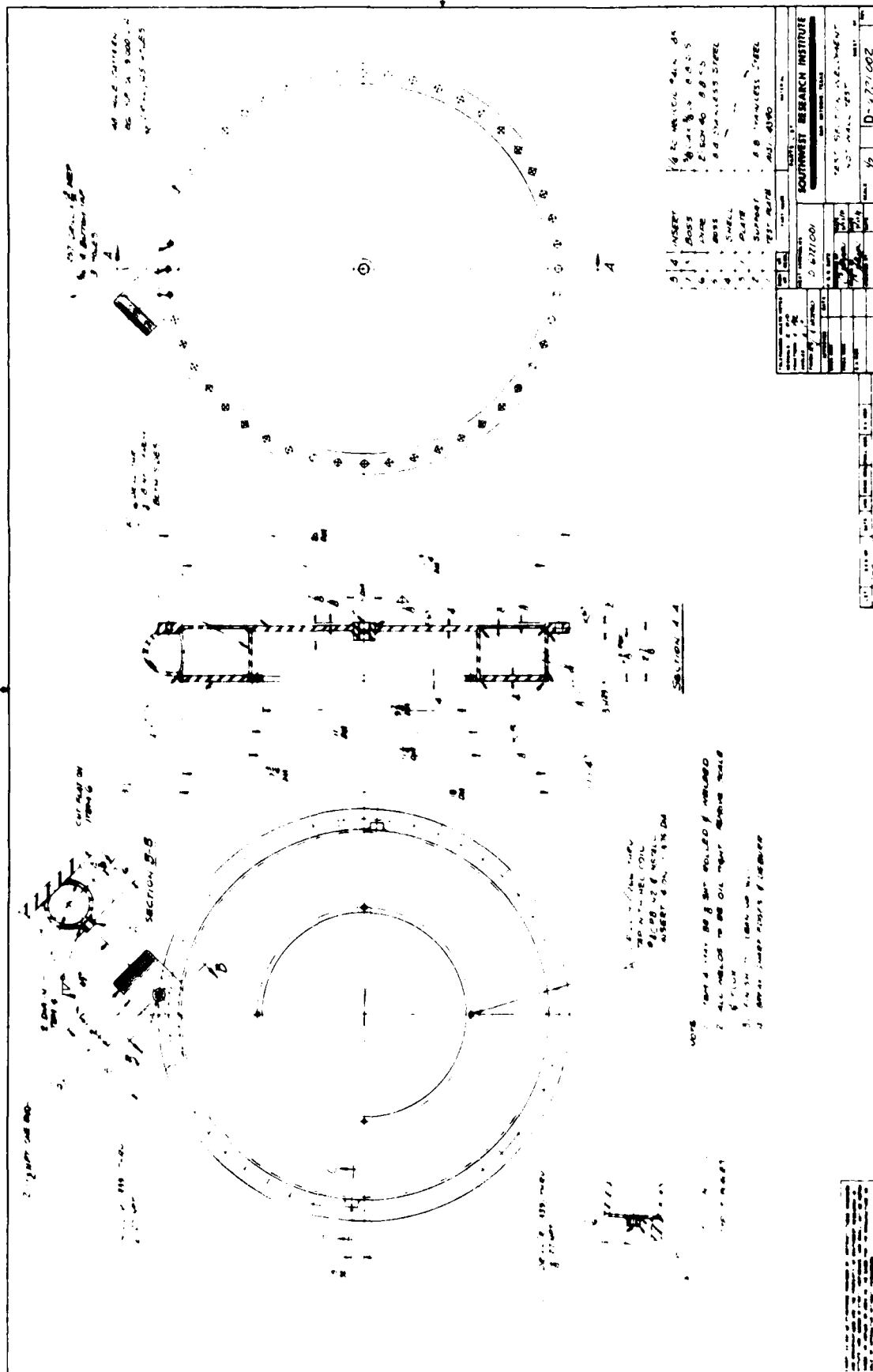
FIGURE 1. DESIGN DETAILS OF HOT-WALL TEST SECTION
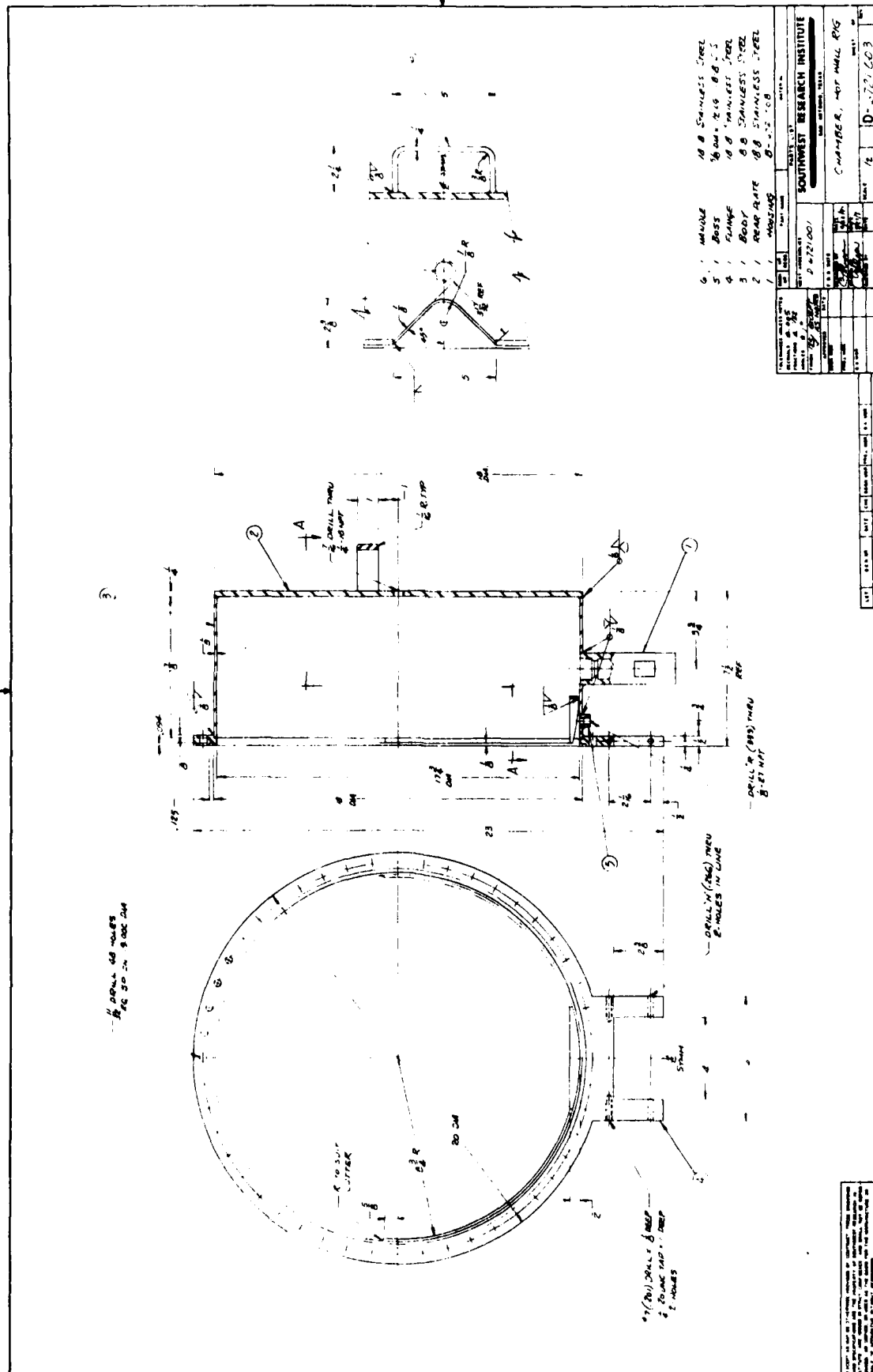
FIGURE 2. DESIGN DETAILS OF HOT-WALL SPRAY CHAMBER

SECTION III

WEAR COUPON SELECTION

The selection process for suitable wear coupons was made through discussions with two major engine manufacturers, and a review of these discussions with the Air Force Project Engineer. General Electric Aircraft Engine Group considered oil-wetted wear metals that could be found in their Air Force inventory engines to be as follows:

Item	Material Specification
Bearing balls/rollers/races	AMS 6490 (M-50) steel
Bearing cages	SAE 4340 steel (Ag plated)
	AMS 4616 bronze (Ag plated)
Gears	SAE 9310 (AMS 6260) steel

Likewise, Pratt & Whitney's Aircraft Government Products Division considered metals typical of their engines to be as follows:

Item	Material Specification
Bearing balls/rollers/races	AMS 6490 (M-50) steel
Bearing cages	Bower 315 alloy (Ag plated)
Gears	M-50 steel

Based on these discussions and the Air Force review, it was determined that wear-coupon material combinations to be employed in this program should be as follows:

- M-50 steel/M-50 steel
- SAE 9310 steel/SAE 9310 steel
- Silver (Ag)/M-50 steel
- AMS 4616 bronze/M-50 steel

As will be shown later in this report, the wear generator employed two wear coupons, namely, an upper wear coupon and a lower wear coupon. The combinations of wear materials shown above consists of both these coupons with the upper material being first and the lower material last, i.e., upper coupon material/lower coupon material. Also, throughout the remainder of the report the materials may simply be referred to as M-50, 9310, silver or Ag, and 4616.

For further specification information the coupon materials were as follows:

M-50 steel - consumable electrode vacuum melted in the annealed state and having an average grain diameter of ASTM No. 8, or finer. Chemical composition in percent was

carbon	0.77-0.85	chromium	3.75-4.25
manganese	0.35 max	molybdenum	4.00-4.50
phosphorus	0.015 max	vanadium	0.90-1.10
sulfur	0.015 max	nickel	0.10 max
silicon	0.25 max	cobalt	0.25 max
copper	0.10 max	tungsten	0.25 max

SAE 9310 steel - fine grain, size 7, vacuum melted, carbon deoxidized, aircraft quality having hardness of Brinell 179. Chemical composition in percent was

carbon	0.100	copper	0.13
manganese	0.58	chromium	1.24
phosphorus	0.006	molybdenum	0.09
sulfur	0.014	nickel	3.45
silicon	0.27		

Silver (Ag) - refined silver meeting ASTM B 413. Chemical composition in percent was

silver	99.99	palladium	0.001
bismuth	0.0005	selenium	0.0005
copper	0.010	iron	0.001
tellurium	0.0005	lead	0.001

<u>AMS 4616 bronze</u> - meeting specification AMS 4616C and having hardness
of Rockwell B 65.   Chemical composition in percent was

copper	91.03	manganese	0.78
zinc	3.52	silicon	3.39
iron	1.21	phosphorus	0.004

SECTION IV

TEST EQUIPMENT AND LUBRICANTS

General

The test equipment used in making the deposition evaluations contained herein consists of a vertically mounted hot-wall test specimen attached to a specimen housing; one side of the hot-wall specimen surface is subjected to a lubricant fog, while the opposite side of the hot-wall specimen surface is in direct contact with a heating fluid which is maintained at pre-determined temperatures. A recirculating test-oil system containing a test-oil pump and wear generator, and adaptable to a filter housing and sampling valves is also part of the equipment. A simple laboratory air supply system completes the necessary equipment for the hot-wall deposition rig.

The hot-wall deposition rig was designed to simulate, as closely as possible, the actual engine operating conditions with regard to oil dispersion, flow rate, and temperatures in the area surrounding the No. 2 rear bearing support of the J57 turbojet engine. The general configuration and principal dimensions of a similar engine part, modified to include an integral fluid-heating tank have been shown and discussed in previous reports.[1,2,3] A photograph showing one of the actual designed and fabricated test-specimen deposit surfaces employed in this work is shown in Figure 3. The deposit surface that is rated is shown between the concentric dashed circles.

The following paragraphs describe the hot-wall deposition rig, the wear generator and wear coupons, the operating procedure, the deposit rating pro-cedure, and trace-metal analysis procedure. Immediately following these descriptions a tabulation of the lubricants employed and supplied by AFWAL is presented.

Hot-Wall Deposition Rig

A schematic of the hot-wall deposition rig is shown in Figure 4. The hot-wall spray chamber consists of a stainless steel cylinder flanged at

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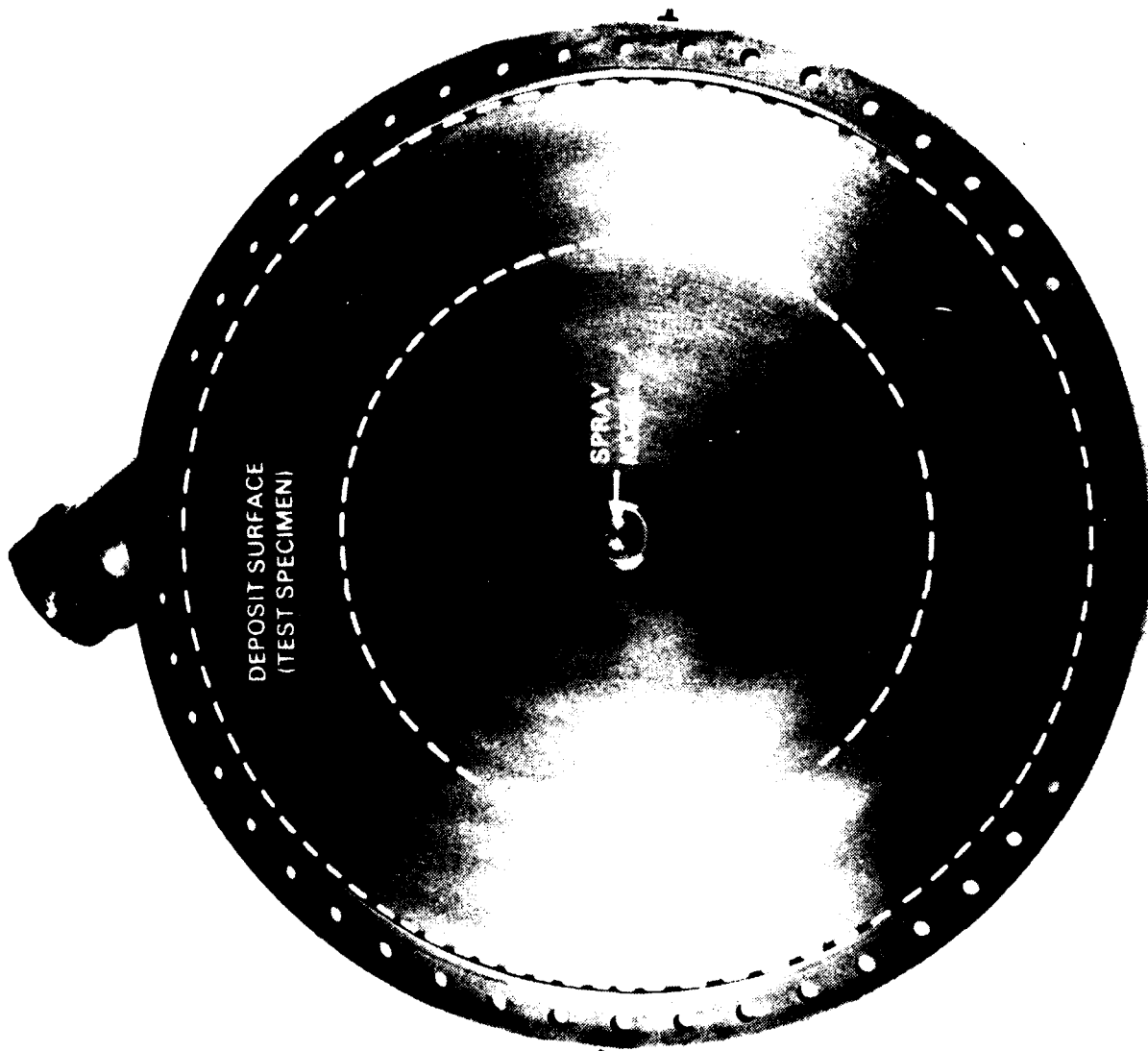
FIGURE 3.   CLEANED DEPOSIT SURFACE PRIOR TO TESTING

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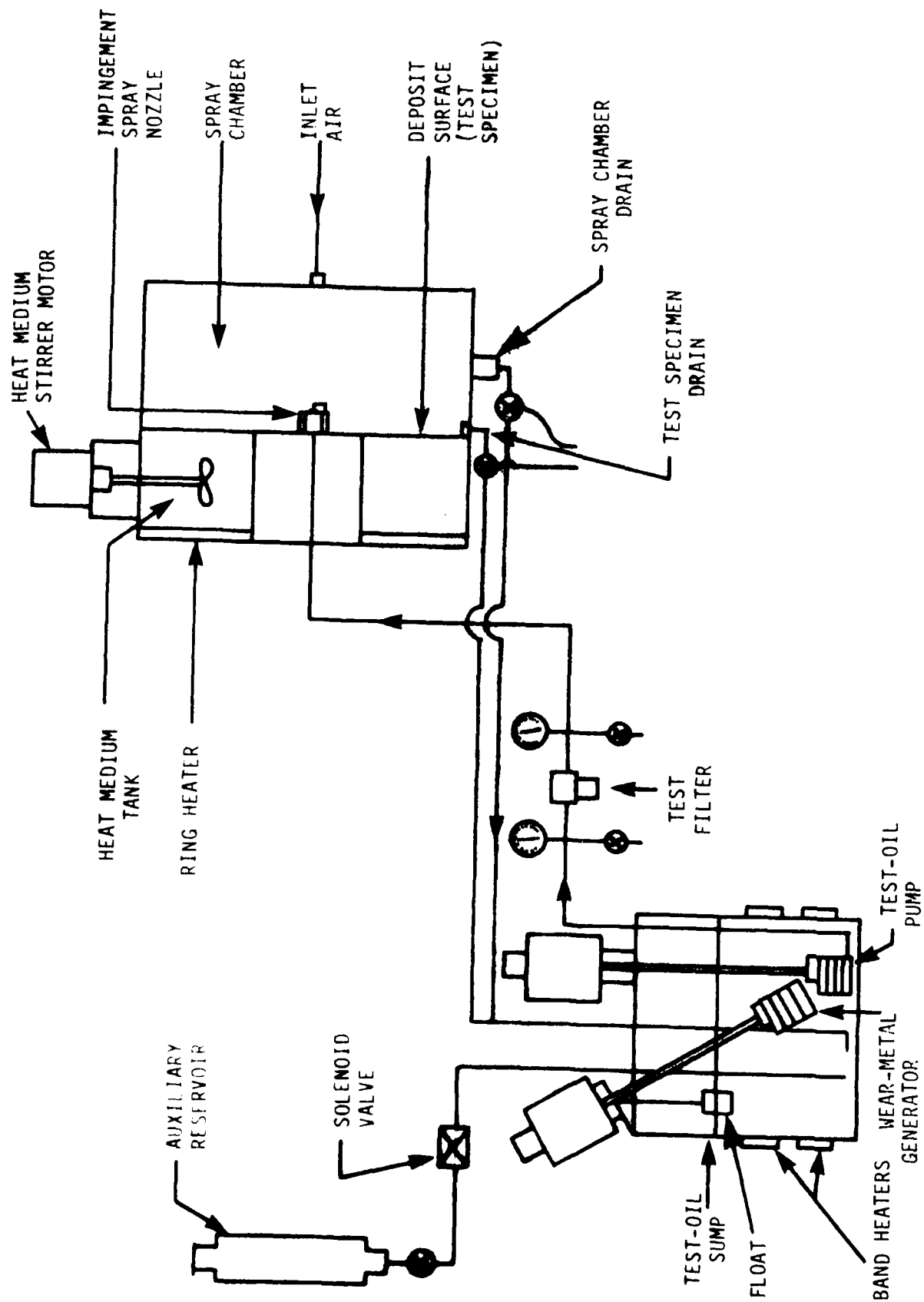
FIGURE 4. SCHEMATIC OF HOT-WALL DEPOSITION RIG

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the end that attaches to the deposit surface (test specimen) and closed at
the opposite end except for the inlet-air connector. The deposit surface
is indirectly heated by means of a heat-medium tank. The fluid used in the
integral heat-medium tank is a reclaimed 5P4E polyphenyl ether. The fluid
is heated by a 4,000-watt ring heater pressed against the tank wall opposite
the hot-wall deposit surface. Agitation of the heating fluid by means of
a stirrer inserted through the tank opening improves the uniformity of tem-
perature throughout the tank.

The test lubricant enters the spray chamber through an impingement spray
nozzle which directs the lubricant fog toward the front of the chamber,
preventing direct contact of large droplets with the test specimen surface.

Provision is made in the spray chamber to separate the lubricant which
contacts and runs off the test specimen surface. This is accomplished by
forming a ridge inside the chamber along the inside diameter of the flange
to which the deposit surface is attached. Lubricant running off the surface
is trapped by the ridge and is diverted to a test specimen drain leading
to a three-way valve. The balance of the lubricant draining from the spray
chamber exits through a 100-mesh screen to the three-way valve.

Air at a controlled moisture content of 20 ± 2 mg of water per liter of
air is admitted to the spray chamber at the inlet-air connector at a rate
of 1.65×10^{-4} m^3/sec (0.35 cfm). The controlled air exits with the lubri-
cant through the drains and back to the test-oil sump. The test-oil sump
consists of a stainless steel container placed within a second container
and having the exterior of the inner vessel coated with a 3.2×10^{-3} m
(1/8-in.) thickness of copper to a height of 7.6×10^{-2} m (3 in.) from the
sump bottom to better distribute the heat. Heat is supplied by two 800-watt
band heaters. A positive displacement gear pump, designated test-oil pump,
is mounted on the sump lid such that the pump is totally submerged in the
test lubricant. This pump is located near the bottom of the sump. For all
tests, a 100-mesh screen is attached to the pump intake. The lubricant pump
is driven by a variable speed electric motor and a pressure control is incor-
porated in the lubricant pressure line to deactivate the pump in the event
of a severe pressure excursion because of spray nozzle plugging.

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To allow for unattended rig operation, makeup oil to the sump is dispensed automatically by use of a feedline with integral solenoid valve leading from an auxiliary reservoir. The solenoid is activated by a microswitch which contacts an oil level rod attached to a float within the test-oil sump. Measurements of the sensitivity of the oil makeup device indicate a test-oil sump volume control capability of 2,300 ± 25 ml.

Figure 4 illustrates the hot-wall deposition rig equipped with test-filter housing and associated pressure gages for determining pressure differential across the test filter. Valves for obtaining test-oil samples both upstream and downstream of the filter are also shown. For tests without filtration these equipment are eliminated from the plumbing arrangement and test-oil samples are taken from the spray chamber drain valve.

Wear Generator and Wear Coupons

The wear-metal generator which operates totally beneath the lubricant level, but above the test-oil pump within the sump, is also shown schematically in Figure 4. The wear-generator components, as shown in Figure 5, include a modified test-lubricant pump, Zenith Model HPB-4647. The pump body is unmodified except for removal of the driven gear. The lower wear coupon rests directly on the pump body. The hub body sits over the lower coupon and the rotating drive plug is placed within the hub body. The upper wear coupon is next in line, followed by the hub top. The hub screws are then inserted to a fixed depth to achieve a measured compression of the load springs. The loading occurs only between the faces of the rotating drive plug and the wear coupons because the hub body thickness dimension has been machined undersized, and with diametrically opposed grooves for metal particles to escape. A typical wear track in a wear coupon is shown in Figure 6.

The device is driven by a variable speed motor and drive shaft which is fitted into the drive plug cavity. Conditions in this program for wear were drive plug rotation at 300 rpm at variable compression loads, depending

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HUB SCREWS AND
LOAD SPRINGS
(1 EACH)

UPPER WEAR
COUPON

ROTATING
DRIVE PLUG
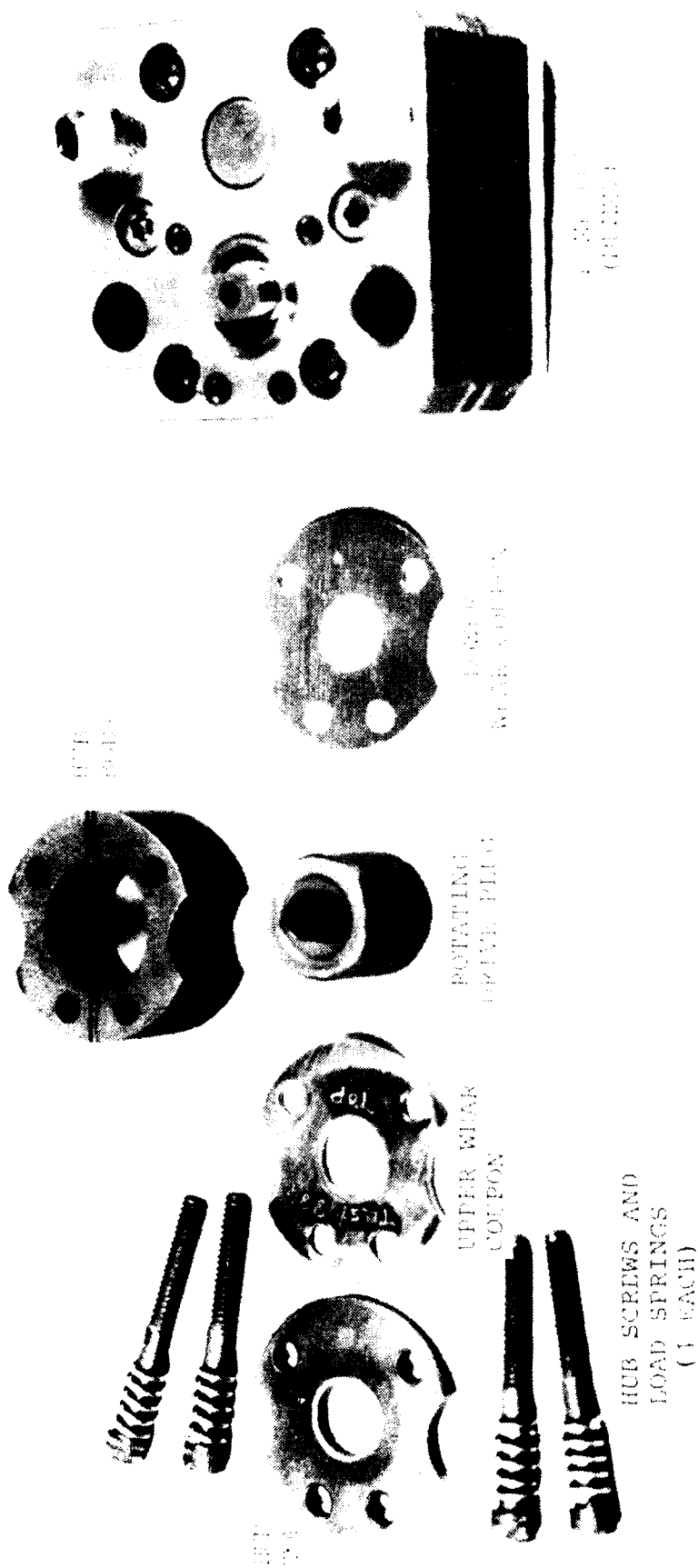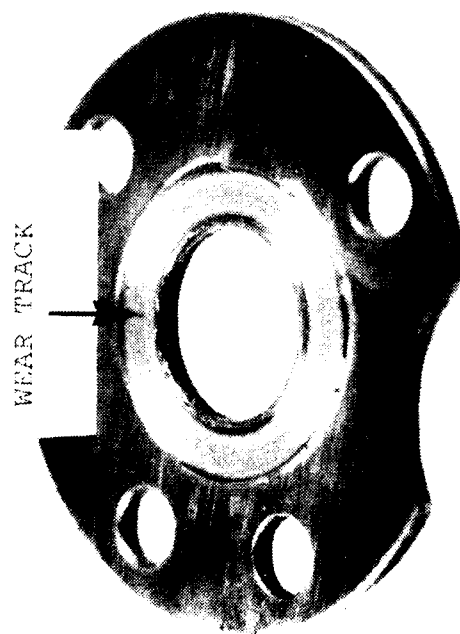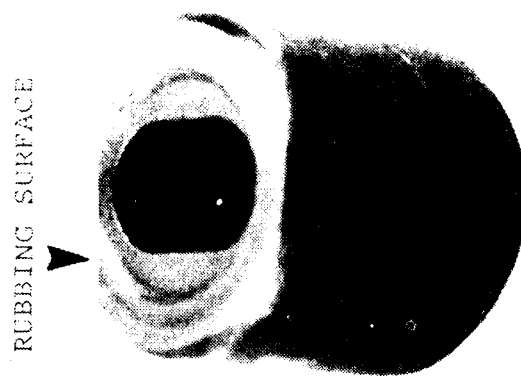
FIGURE 6. TYPICAL POSTTEST WEAR TRACK AND MATING WEAR SURFACE ON WEAR-GENERATOR COMPONENTS

on the coupon materials, as follows:

Wear Coupon Material	Initial Total Normal Load, newtons (lb)	Initial Load Pressure, x 10⁻⁶ Pa (psi)
M-50/M-50	890 (200)	5.96 (864)
9310/9310	445 (100)	2.98 (432)
Silver/M-50	890 (200)	5.96 (864)
4616/M-50	890 (200)	5.96 (864)

This was done in an effort to adjust the amount of wear realized during testing, because the M-50 steel coupons were harder than 9310 steel coupons and consequently tended to wear less. Details of coupon materials have already been discussed in Section III of this report. For tests without wear, the wear coupons were replaced with carbon coupons, which are normally installed in a new pump; the assembled generator was placed in the test-oil sump, but did not rotate during the test.

Figure 7 is a photograph illustrating the assembled components of the test-oil sump just prior to installation in the sump container. As shown, most of the components are attached to the sump lid which is then attached to the top of the sump and consequently appears schematically as shown in Figure 4. Shown in Figure 7 is the test-oil pump, wear generator with attached wear-coupon load springs, float, thermocouples (2 ea), test-oil pump strainer, drive shafts (2 ea), and the associated plumbing. The drive motors and gearboxes (not shown) for both the test-oil pump and wear generator are installed on the topside of the cover after it is attached to the test-oil sump. Most of the oil-wetted components, except the pump bodies and float are fabricated of stainless steel. The deposit surface (test specimen) shown in Figure 3 and shown schematically in Figure 4 is made of AMS 6415 (SAE 4340) steel as discussed in Section II of this report.

Micronic Filter Elements

The mitigation of wear-metal effects phase of this program consisted of performing tests with 15 µm and 3 µm filtration. Details of these micronic
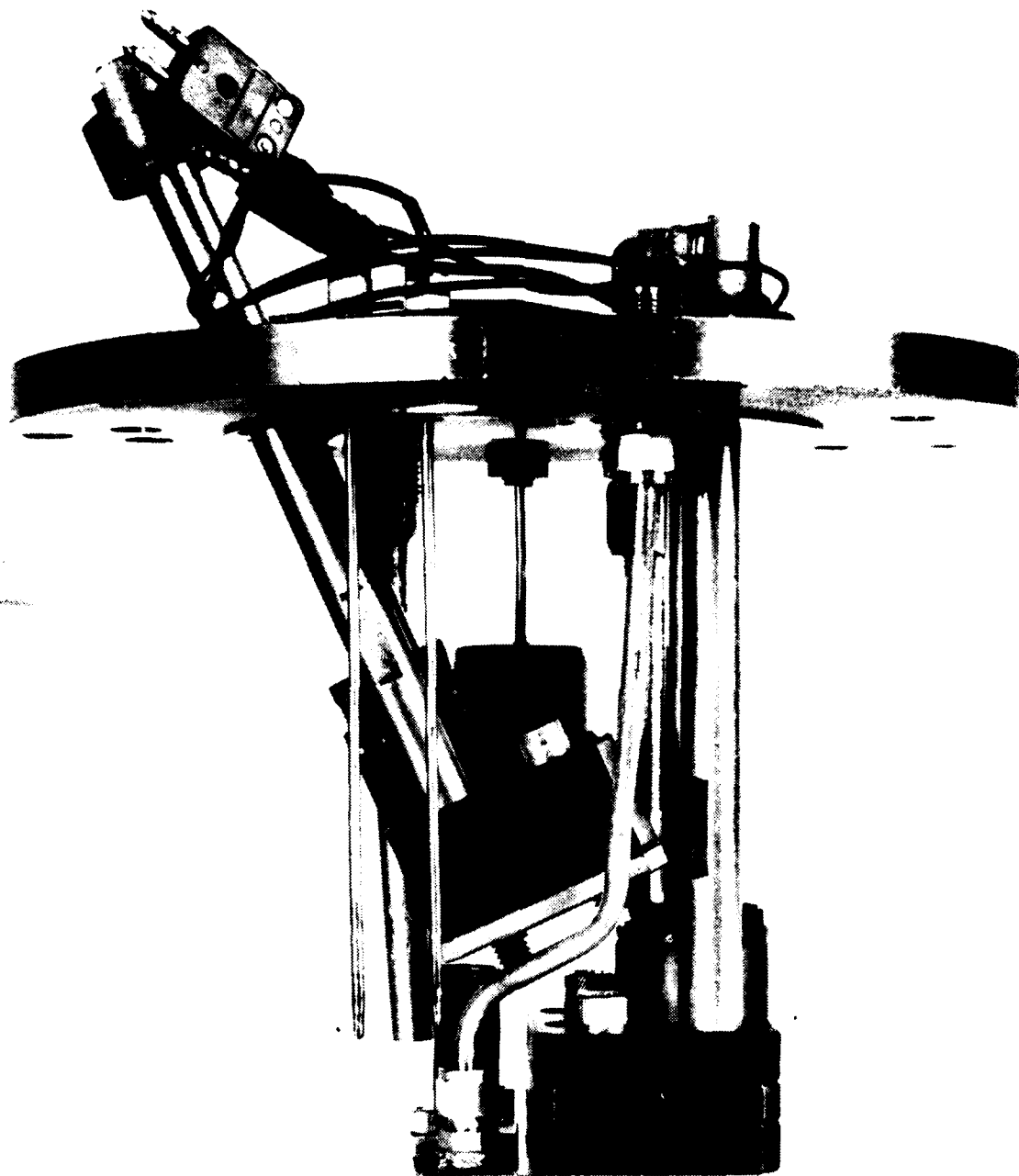
FIGURE 7.   ASSEMBLED COMPONENTS OF TEST-OIL SUMP

filters have been discussed extensively in a technical report[1] for a companion program and will not be repeated in its entirety herein. On the basis of information gathered on the companion program two element ratings were also selected for use in this program. These elements were procured from Aircraft Porous Media (APM). Using outdated terminology the two filter ratings would be described as 0.9 μm nominal, 3 μm absolute and 10 μm nominal, 15 μm absolute. Current filtration technology no longer recognizes the use of such ratings since values vary with manufacturer's interpretations. Presently, the preferred criterion of filter capability is the beta ratio (β_x) defined as the ratio of the number of upstream particles larger than x μm to the number of downstream particles larger than x μm, for a given fluid volume. As an illustration, a β_3 of 100 signifies that if 100 particles of size greater than 3 μm enter the filter, no more than one particle of size greater than 3 μm will pass the filter for an equal fluid volume.

For ease of identification and discussion, continued reference to the two elements as 3 μm and 15 μm will be used; however, it should be recognized that these designations have little technical basis. For example, APM has supplied beta ratio plots for the two elements as shown in Figure 8. It is of interest to note that the 3 μm element has a β_3 of 500, while the 15 μm element shows a β_{15} of 1000. Criterion used for changing the filter during filtration testing was when the differential pressure across the filter, as determined by the pressure gages, reached 6.2×10^5 Pa (90 psi).

Operating Procedure

Hot-wall deposition tests are accomplished by first diligently cleaning all of the oil-wetted surfaces. The deposit surface (test specimen) is cleaned to a metallic luster by scrubbing with appropriate cleaning materials. Then the rig is assembled and the heat-medium tank charged with 5P4E polyphenyl ether. The test-oil sump and auxiliary oil reservoir are charged with 2,300 and 1,000 ml of test lubricant, respectively. The test-oil pump is turned on and the air supply to the specimen housing is set at 1.65×10^{-4} m^3/sec (0.35 cfm). The test-oil pump is normally set at a gage pressure of 2.8×10^5 Pa (40 psig) initially and is later adjusted to the required pressure to
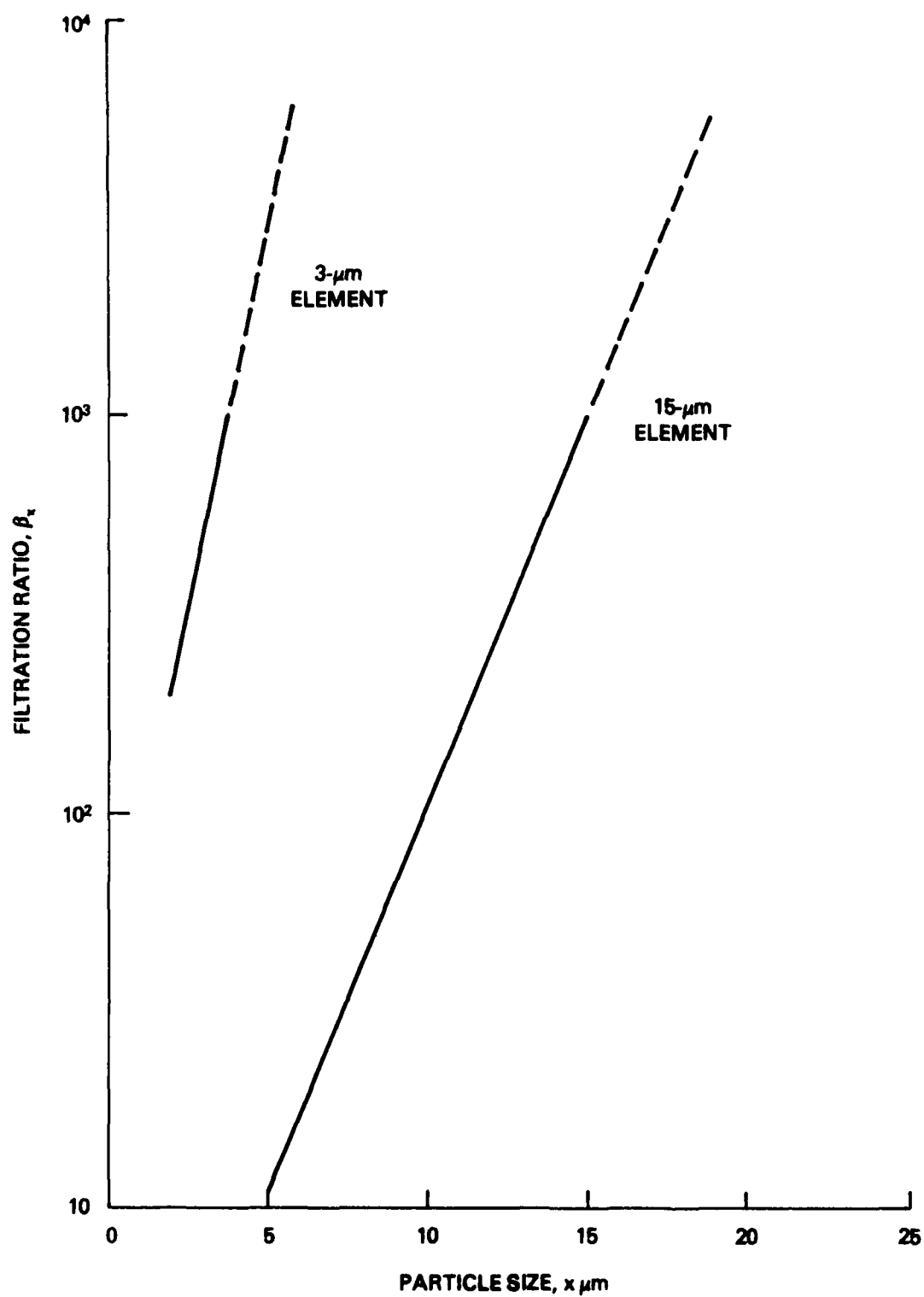
FIGURE 8. VENDOR'S ESTIMATED BETA VALUES FOR TEST FILTER ELEMENTS

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provide 300-ml/min oil flow to the spray chamber. The test-oil sump and heat-medium tank heaters are then turned on to increase the sump temperature to 177°C (350°F). The temperature of the heat medium rises considerably faster and is brought up to 293°C (560°F) in steps as the sump temperature is reaching 177°C (350°F). The required temperatures are normally obtained in 30 to 45 minutes. After the test-oil flow rate is set, the solenoid valve of the automatic oil makeup system is adjusted to maintain the proper level of lubricant in the test-oil sump. For tests having wear, the wear generator is started and set at 300 rpm when the proper temperatures are obtained. Start of the test is when these temperatures are within 6°C (10°F) of the sought temperatures and are being controlled by the thermocouple-instrumented controllers. For filtration tests the appropriate filter (3 μm or 15 μm) is installed in the filter housing prior to starting heat-up. When changing filters during test, the test-oil pump is stopped and the preweighed-new filter installed in the filter housing. This requires approximately five minutes.

The normal test duration is 48 hr of continuous operation, during which the test-oil sump temperature and the heat-medium tank temperature are controlled automatically. The test-oil-in temperature is measured just ahead of the spray nozzle, but is not controlled. Generally, this temperature is less than 6°C (10°F) lower than the sump temperature. A 104-watt heating tape is normally employed on the test-oil line between the sump and spray nozzle to maintain this temperature within the 6°C (10°F) temperature spread. For filtration tests it was found that the heating tape was necessary to prevent exceeding the allowed temperature drop. All exterior oil-in lines are wrapped with insulation after installing the heating tape. Also, the outside of the heat-medium tank is wrapped with insulation to aid in the prevention of heat losses.

Lubricant samples are drawn from the spray-chamber drain (40 ml for non-filtration and 20 ml for filtration with wear) for 40°C (104°F) kinematic viscosity and neutralization number determinations. These are taken at 16-hr, 24-hr and 48-hr (end of test) test times. For filtration with wear tests, samples are also taken upstream (before filter) and downstream (after filter)

from the filter at the same times. These samples are 10-ml each and are employed for trace wear metal determinations by atomic absorption spectrometer.

When used, the wear coupons are prepared as follows:

1. Rinse and wipe with swab using toluene
2. Oven dry
3. Cool for minimum of 30 min and weigh to nearest milligram.

The coupons are then assembled in the wear generator. Posttest treatment of wear coupons was as follows:

1. Rinse with heptane
2. Electrolytic clean
3. Dip or rinse in deionized water, isopropyl alcohol, and toluene in that order
4. Oven dry
5. Cool for minimum of 30 min and weigh to nearest milligram.

Deposit Rating Procedure

The deposit rating procedure, used to describe numerically the deposits on the hot-wall specimen posttest, is similar to that used in the 48-hr bearing deposition test[4], the primary differences being that for the hot-wall only one surface of one item is inspected, and in the case of sludge over carbon, the carbon is employed for computing the rating.

A demerit rating number is selected to identify the different types and thicknesses of deposits present. Demerit values range from 0-20, defined as follows:

Deposit Type	Demerit Rating Number		
	Light	Medium	Heavy
Varnish	1	3	5
Sludge	6	7	8
Smooth carbon	9	10	11
Crinkled carbon	12	13	14
Blistered carbon	15	16	17
Flaked carbon	18	19	20

This demerit number is multiplied by a number from 0 to 10, corresponding to the percent of the area, 0 to 100 percent, covered by that deposit type. In the event that more than one type of deposit is present on the rated area, the deposit rating is then the total of the individual rating values necessary to account for 100 percent of the rated area. In any event, double ratings, such as sludge over varnish, are not used. The deposit rated is that which is visible without the removal of another deposit, except in the case of sludge over carbon. In such instances, the more severe deposit type is used in the rating calculation.

Trace-Metal Analysis Procedure

Lubricant Samples. Trace-metal analyses of lubricant samples were performed on a Perkin-Elmer Model 403 atomic absorption spectrophotometer with a digital concentration readout. Lubricant samples were diluted in xylenes and analyzed against standards prepared from Conostan metallo-organic compounds in xylenes. Sensitivities for this technique are as follows:

Wear Metal Element	Sensitivity,* mg/ℓ	Linear Working Range, mg/ℓ
Fe	0.10	5.0
Cu	0.08	5.0
Ag	0.06	4.0

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* Amount of material that would give 1 percent signal above background levels.

Repeatability is entirely dependent on sample type, viscosity, composition, particle size of trace metals, and age. Generally repeatability is ± 1-3 percent of trace metal concentration, i.e., a 100 ppm result could be 97-103 ppm.

Deposit Scrapings. Analyses were performed with an EDAX Model 707B energy dispersive X-ray analyzer to yield quantitative results. Samples were washed with filtered heptane, then finely ground, weighed, and suspended in a known volume of heptane. The aliquots were collected on 0.45 μm membrane filters. Standards were prepared by depositing weighed quantities of oxides and salts of metals on membrane filters in the same manner. The precision by this method is 2 percent and a minimum of approximately 10 ppm of an element can be determined by the technique.

Test Lubricants

Specific details concerning lubricant formulation are rarely available due to the proprietary interests involved. Table 1 presents a listing of the eight lubricants included in this program with initial viscosity and neutralization number data and available information on specification type.

TABLE 1. DESCRIPTION OF TEST LUBRICANTS

Lubricant Code	Viscosity, cSt, 40°C (104°F)	Neutralization Number, mg KOH/g	Description
O-71-11	12.0	0.26	MIL-L-7808G
O-76-9	12.3	0.58	MIL-L-7808G
O-77-4	13.3	0.30	MIL-L-7808G
O-79-16	12.4	0.20	MIL-L-7808H
O-79-17	13.4	0.05	MIL-L-7808H
O-79-20	14.0	0.13	MIL-L-7808H
O-82-2	12.8	0.05	MIL-L-7808G
O-82-3	14.2	0.03	MIL-L-7808 Type

SECTION V

TEST SUMMARY DATA

General

Immediately after construction of the two new test rigs, several tests
were performed wherein reproducibility between this program and the concurrent
companion program was evaluated. After this evaluation eight lubricants
were deposition tested using the two newly constructed rigs. The lubricants
were evaluated under five different test conditions, namely, without wear,
M-50/M-50 wear, 9310/9310 wear, silver/M-50 wear, and 4616/M-50 wear, all
without filtration. Two or more tests for all conditions were performed with
the majority of the conditions being duplicate tests. After completing these
preliminary tests, a brief statistical study was made to determine which
lubricants under what test conditions should be utilized for the mitigation
of effects study. Initially it was planned to include some of the mild-steel
wear tests from the companion program study in this analysis, but temperature
calibrations showed that the hot-wall section of the rigs on this program were
maintained slightly higher and more uniform in temperature than the companion
program hot-wall surfaces. As a result some of the lubricants common to both
programs tended to degrade significantly, as evidenced by viscosity and
neutralization number measurements of the test lubricants, on this program,
but had not shown the same degradation on the companion program. Also, one
lubricant investigated in this program was not employed in the companion
program and two lubricants employed in the companion program were not used
in this program. In other words, only seven of the lubricants were common
to both programs. As a result of these discrepancies, it was decided to not
include mild-steel wear tests from the companion program in this analysis.
After the preliminary brief statistical study, five lubricants having wear
and micronic filtration were tested and analyzed in the mitigation of wear-
metal effects phase of the program. The complete tables of test summary
data, both without and with micronic filtration, for all eight lubricants
are presented in the Appendix of this report.

In this section of the report and also in the Appendix, tables and plotted graphs of data pertaining to the eight lubricants are presented. The data, in certain presentations, will be shown in the order of the lubricant code numbers as assigned at the AFWAL, and do not indicate a preference or preferential treatment of any one lubricant over another.

Reproducibility Evaluations

Initially lubricant O-79-17 was identified in the revised test plan for reproducibility testing between this program and a concurrent companion program.[1] Two hot-wall tests were performed and comparison of the test results showed favorable agreement. As shown in Table 2, it can be seen that the deposit ratings and neutralization number (NN) changes have fairly good agreement. One of the viscosity increases (Test No. 102-2-28) for a new rig constructed on this program differed considerably, but it was probably lowered because of dilution with new oil during flow check measurements. On the other hand, the dilution did not appear to affect the NN similarly. The specimen drain rates for the new design rigs are somewhat higher than for the old design. Later tests employing lubricants O-79-16 and O-79-20, and also shown in Table 2, did not show nearly as good reproducibility of deposit ratings, although viscosity and NN results compared fairly well. Lack of agreement in deposit ratings between the "old design" and "new design" hot-wall deposition test rigs for these two lubricants prompted a search for explanations. At first observation it appeared that much of the disagreement was attributable to the tin-plated floats in the lubricant sumps. Therefore it was decided to investigate the effect of exchanging the floats between the rigs. The stainless steel floats were installed in the old design hot-wall oil sumps and the old tin-plated steel floats installed in the new design rigs. Since lubricant O-79-20 appeared to be extremely sensitive to both wear metal and trace metal, it was selected for these float-exchange tests. Table 2 compares these test results for the two variations of rig designs along with the previously discussed data. As shown in Table 2, significant reductions in deposit ratings occurred for tests having stainless steel floats in the old rigs. Also shown is an increase in deposit ratings for tests having the old tin-plated steel floats (as opposed to stainless steel) in the new

TABLE 2. COMPARISON OF HOT-WALL DEPOSITION TEST DATA BETWEEN TWO RIG DESIGNS

Designation	Deposit Rating	40°C Vis Incr, %	NN Change mg KOH/g	Specimen Drain, ml/min	Test No.
Lubricant O-79-17					
Old design	40.0	14.0	0.46	20	945-3-16
	41.0	15.5	0.48	26	946-4-10
New design	36.0	16.1	0.47	33	101-1-27
	41.0	9.4[a]	0.51[a]	29	102-2-28
Lubricant O-79-16					
Old design	27.0	8.4	0.28	22	901-4-6
	27.0	8.2	0.23	16	912-4-9
New design	45.0	9.8	0.35	27	107-1-29
	45.0	9.8	0.32	25	108-2-30
	35.0[b]	7.2	0.30	24	111-1-29
	29.0[b]	8.1	0.20	20	112-2-30
Lubricant O-79-20					
Old design	33.0	7.5	0.29	26	967-3-16
	30.0	6.3	0.24	21	968-4-17
	35.0	7.6	0.33	22	971-3-16
	24.0[b]	6.9	0.30	19	981-3-16
	20.0[b]	7.6	0.32	18	982-4-19
New design	58.5	8.4	0.39	26	104-2-30
	75.0	7.9	0.37	27	105-1-29
	49.0[b]	8.5	0.41	28	109-1-29
	46.5[b]	8.7	0.43	30	110-2-30
	54.0[c]	5.2	0.43	28	119-1-29
	53.0[c]	6.3	0.41	30	120-2-30

(a) Questionable results because of accidental dilution of lubricant in sump during flow check.
(b) Used stainless steel float in lubricant sump.
(c) Used "old" tin-plated float in lubricant sump.

rigs. On the other hand, the old tin-plated floats in the new rigs gave deposit ratings lower than the new design which contained newly fabricated tin-plated floats. This implies that repeated usage of the tin-plated floats had decreased the catalytic effect on deposition. Regardless, there appears to be an influence even after many tests. At this time selected lubricant samples from these tests were submitted to the laboratory for trace metal analyses by emission spectroscopy in an effort to provide further substantiating results which would enlighten the effect of trace metals on lubricant deposition. Meanwhile, stainless steel floats to minimize the catalytic effect of unwanted trace metals were employed for further testing on this program.

Emission spectroscopy analyses on selected posttest lubricant samples failed to provide significant differences in trace metals for tests using three different float conditions (stainless steel, "new" tin-plated steel and "old" tin-plated steel). It was then determined that the emission spectrometer model used will not distinguish tin in oil samples of less than 10-12 ppm. Since, all of the submitted samples, as well as a new oil sample, displayed 9-12 ppm tin, no discrepancies could be distinguished.

Comparison of hot-wall test specimen temperatures between the new design and old design rigs was performed by employing thermocouples spotwelded to the heated surfaces. Two thermocouples were placed on the hot-wall surface approximately as shown on the sketch in Table 3. Temperature of the heating fluid (5P4E polyphenyl ether) was controlled and recorded at approximately 560°F. Temperatures of the heating fluid and the hot-wall test specimen were recorded after thermal equilibrium was established at 16, 24, 40 and 48 hr. The averaged values for the four rigs as determined by one test for each rig are presented in Table 3. It can be seen that less difference between the temperature of the two locations on each of the new rigs was determined, these values being 8° and 6°F for Rig No. 1 and 2, respectively. The differences for the old rigs were 10° and 19°F for Rig No. 3 and 4, respectively. An effort to improve or decrease this difference was made by increasing the length of the drive shaft on the stirrer located in the heating fluid tank, but to no avail. Since more vibration was associated with use of the longer shaft, the original configuration was again used for agitation of the heating fluid. It can also be seen from Table 3 that the average temperature as

TABLE 3. COMPARISON AND VERIFICATION OF HOT-WALL SURFACE AND HEATING FLUID TEMPERATURES
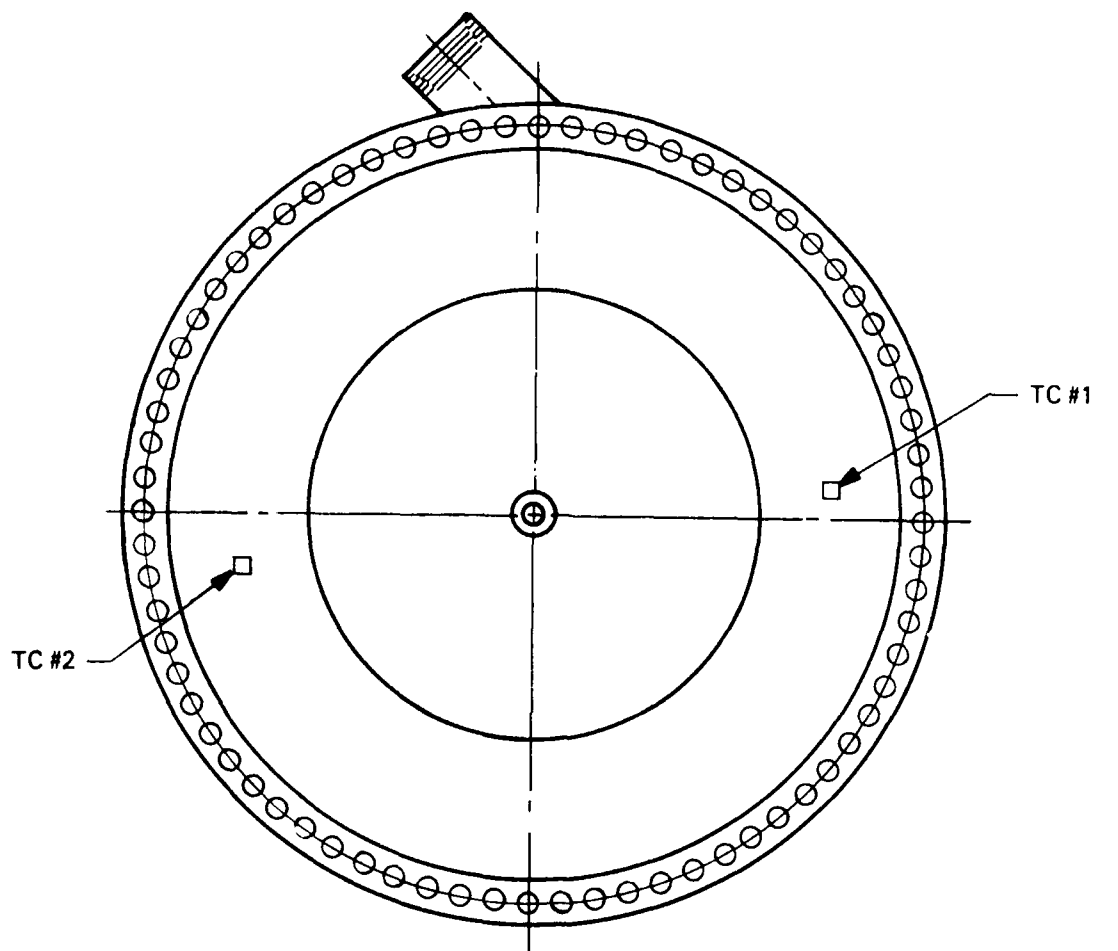
DESIGNATION	AVG HEAT FLUID TEMP, °F	AVG TC #1 TEMP, °F	AVG TC #2 TEMP, °F
COMPARISON BETWEEN TWO RIG DESIGNS			
RIG NO. 1 (NEW DESIGN)	560	548	540
RIG NO. 2 (NEW DESIGN)	561	549	543
RIG NO. 3 (OLD DESIGN)	558	544	534
RIG NO. 4 (OLD DESIGN)	559	550	531
VERIFICATION FOR NEW DESIGN			
RIG NO. 1, SHAKEDOWN PERIOD	560	548	540
RIG NO. 1, VERIFICATION TEST	561	548	541
RIG NO. 2, SHAKEDOWN PERIOD	561	549	543
RIG NO. 2, VERIFICATION TEST	562	547	538

measured by thermocouple No. 1, for the new rigs, was consistently $8^\circ F$ below
the recorded temperature of the heating fluid, whereas the old rigs displayed
a difference of 14° and $9^\circ F$. Approximately nine months later, after numerous
tests, the hot-wall test specimen temperatures were again checked for verifi-
cation purposes. A comparison of the temperatures obtained both during shake-
down and again at verification are also presented in Table 3. As shown the
results repeated very well.

Hot-Wall Test Results

Immediately after completing the preliminary testing of the eight lubri-
cants, under five different wear metal conditions, a brief statistical study
was made in an effort to determine the condition for the mitigation of effects
testing. From this study the deposit rating means for the eight lubricants
are shown in Figure 9. From this figure it appears that lubricant 0-71-11
behaves differently than the other lubricants and also consistently produced
lower deposit ratings. Also, lubricant 0-82-2 appeared to be somewhat in-
sensitive to wear metals as a deposition catalyst. It had the highest de-
posit rating of all eight lubricants in nonwear tests, but illustrated small
increases only, in deposition with M-50/M-50, 4616/M-50, or silver/M-50 wear.
The 9310/9310 wear did not produce as significant an increase in deposition
as was observed for the other lubricants. Lubricant 0-76-9 was employed in a
companion program, during March-December 1981, for hot-wall deposition testing
to establish the effects of micronic filtration on lubricant degradation. At
that time it was established that the lubricant was undergoing storage changes
as evidenced by an increasing neutralization number. It had increased from
0.24 mg KOH/g in May 1975 to 0.34 mg KOH/g in March 1981 and continued to
increase to 0.47 mg KOH/g in January 1982. Therefore, the lubricant, although
scheduled for deposition testing in this program, was put on "hold" by the
AFWAL project engineer. It remained on "hold" until January 1983 when the
project engineer selected it as the eighth and final lubricant for evaluation
on this program. At that time the neutralization number for 0-76-9 in cold
storage was determined to be 0.58 mg KOH/g. Because of these conditions,
lubricants 0-71-11, 0-76-9 and 0-82-2 were eliminated from the mitigation of
wear-metal effects phase of the program.
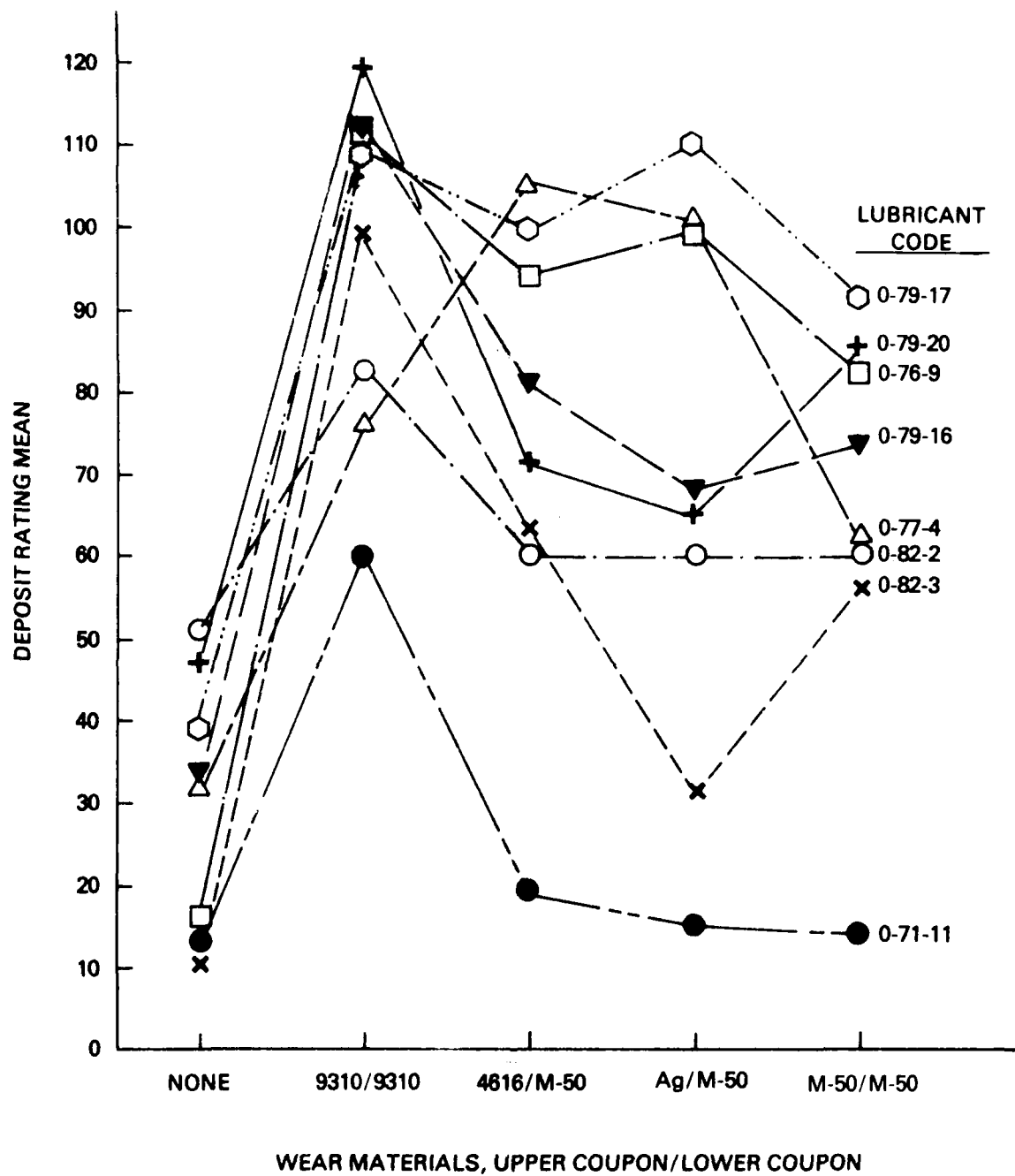
FIGURE 9. MEAN DEPOSIT RATINGS FOR EIGHT LUBRICANTS

Therefore, the deposit rating means for the remaining five lubricants having five wear-metal conditions were replotted in a rearranged configuration as shown in Figure 10. As seen in this figure two of the lubricants 0-79-16 and 0-82-3 had similar trends in deposit ratings with both increasing approximately the same for the wear-metal arrangement along the abscissa. 0-79-16 does have significantly higher deposition than 0-82-3. In the previous figure and also this figure, the data points for each lubricant have been connected by lines for clarification purposes. Also, it might be feasible to employ the lines to determine expected deposit ratings for combinations of the wear metals shown. In other words, deposit rating for a combination of 9310 wear with 4616 and M-50 wear might be expected to fall somewhere between these two plotted points for the particular lubricant of interest. Lubricant 0-79-20, as shown in Figure 10, also has a trend in deposition similar to both lubricants 0-79-16 and 0-82-3. The main dissimilarity being the low deposit rating for 4616/M-50 wear. On the other hand, both lubricants 0-77-4 and 0-79-17 show deposition characteristics somewhat similar to each other, but significantly different than the three other lubricants.

As a matter of information the deposit rating means for both groups of eight and five lubricants employed in Figures 9 and 10 were averaged for each wear-metal condition and the results are shown in Figure 11. The wear metals were rearranged (M-50/M-50 before Ag/M-50) in the order of increasing deposition. As can be seen there is very little difference between the M-50/M-50 and Ag/M-50 results and for all practical purposes can be assumed to be the same. As previously noted, the 9310/9310 steel wear gave considerably higher deposition than the other combinations of wear metals tested. The averaged data points in this figure have not been connected by a line; the plot merely illustrates the averaged value for each condition and its comparison to the other wear-- metal conditions studied.

From the data shown in Figure 10 a list of testing conditions for the mitigation of wear metal effects phase of the program was selected. This list is shown in Table 4. An effort was made to cover all combinations of wear metals studied, with the majority of the effort being on 9310/9310 wear metal since it had produced the highest deposition for most of the lubricant-material combinations. Also more effort was expended on 15 μm filtration in

33
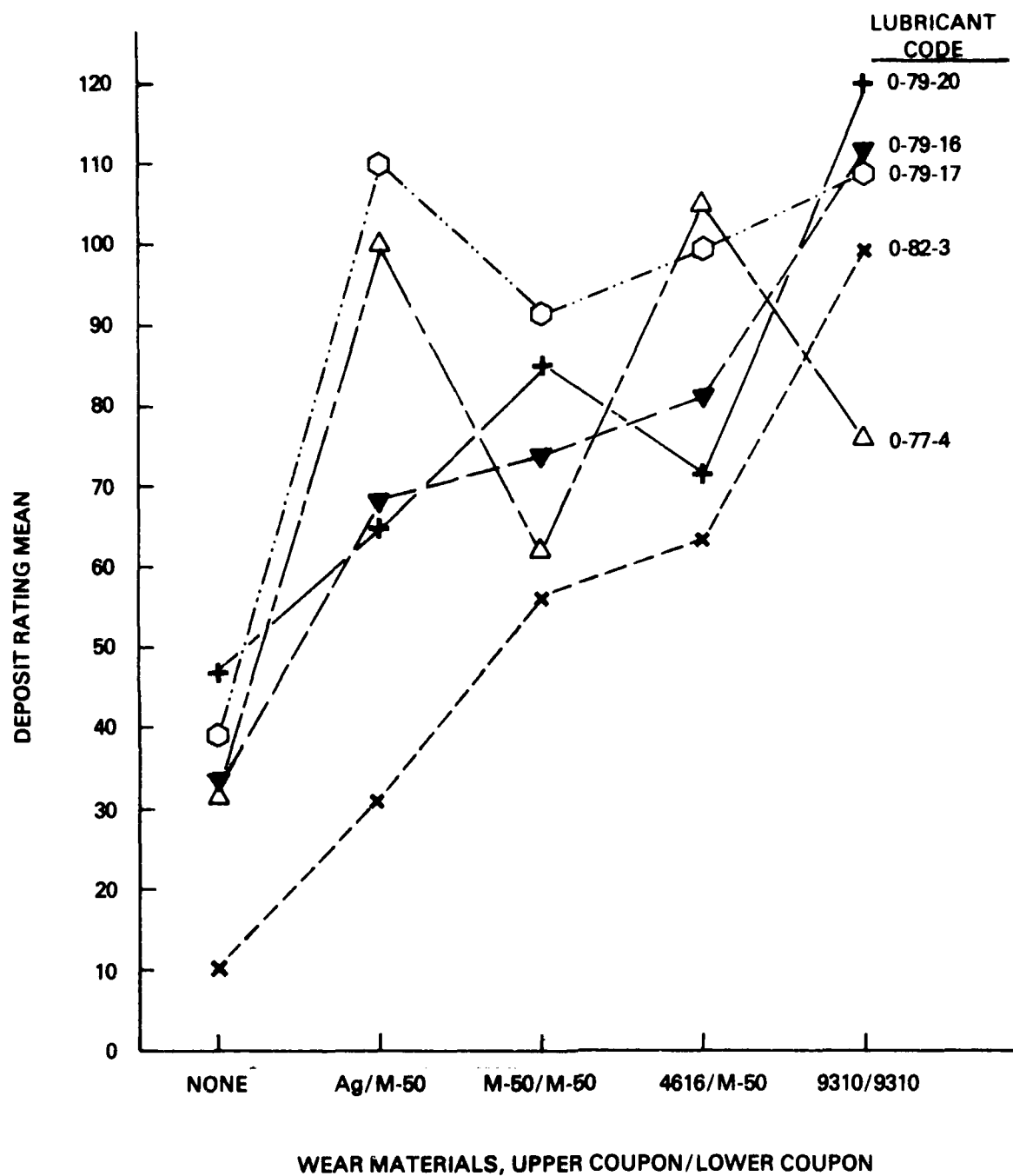
FIGURE 10.   MEAN DEPOSIT RATINGS FOR FIVE LUBRICANTS FOR
MITIGATION OF EFFECTS STUDY
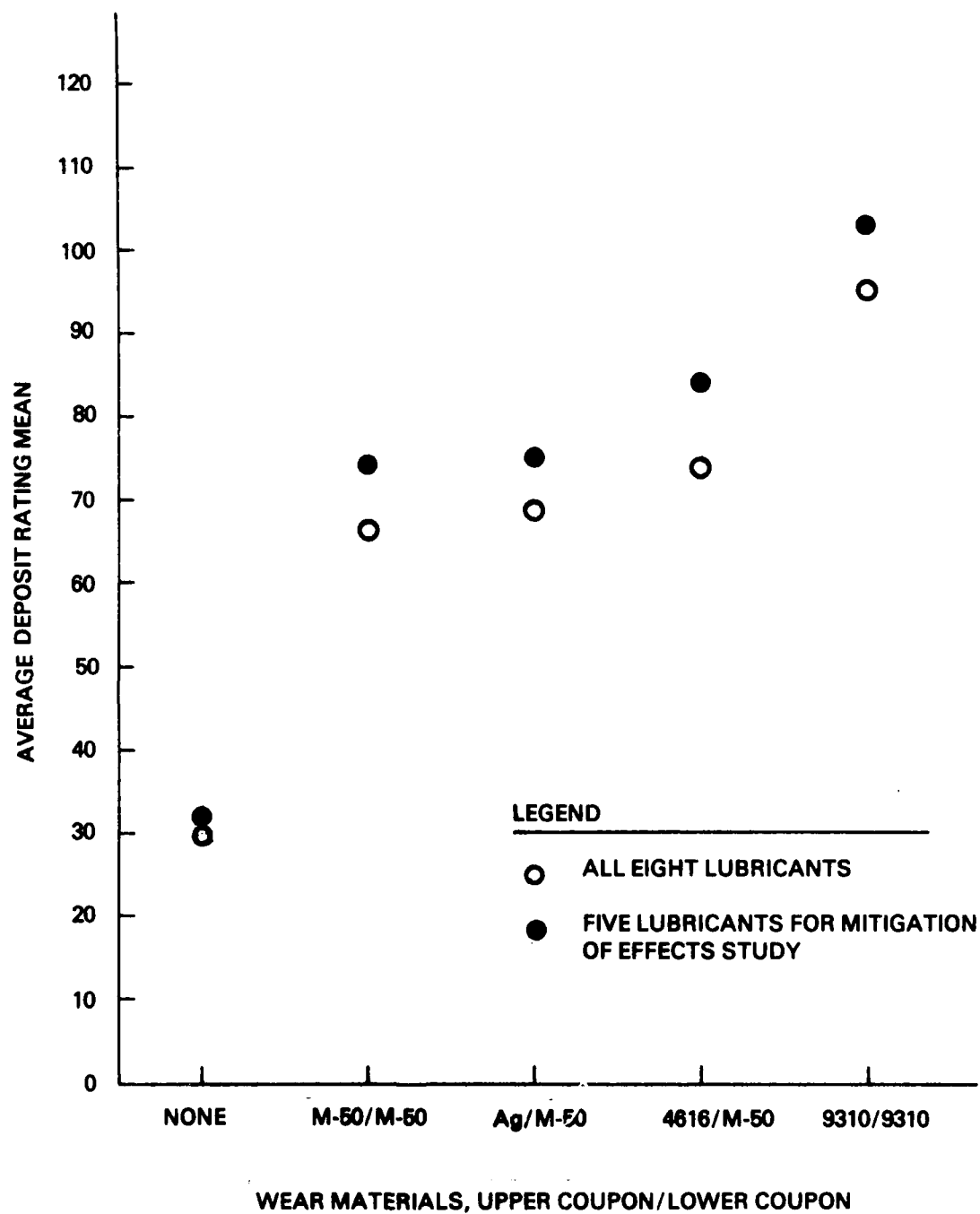
FIGURE 11. AVERAGED DEPOSIT RATINGS FOR SYNTHETIC TURBINE ENGINE LUBRICANTS

TABLE 4. TESTS FOR MITIGATION OF WEAR-METAL EFFECTS

Lubricant Code	Wear Coupon Materials, upper/lower	Filtration Level, μm
0-77-4	4616/M-50	15
0-77-4*	4616/M-50	3
0-79-16	9310/9310	15
0-79-16	9310/9310	3
0-79-17	M-50/M-50	15
0-79-17	Silver/M-50	15
0-79-20	9310/9310	15
0-79-20	9310/9310	3
0-82-3	9310/9310	15

* Single test.

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the mitigation of effects phase of the program. This was prompted by the companion program[1] on the effects of filtration on lubricant deposition wherein mild-steel wear was investigated and had shown that while deposit ratings with 15 μm filtration were slightly higher than with 3 μm filtration, there was no significant difference.

Comparison of Filtration and Nonfiltration Tests

After completing the filtration testing, the averaged hot-wall test results for the five fluids investigated were compared with the averaged non-filtration results and the observations made were as follows:

- Tests for no filter, 15 μm and 3 μm levels of filtration using 4616/M-50 wear and employing lubricant 0-77-4 all showed high deleterious effects in deposits. There appeared to be some improvement when using filtration, but deposit ratings remained very high and no significant difference was noted between 3 μm and 15 μm filtration. Also, deleterious effects in viscosity and NN increases remained even with filtration, and extreme scatter was noted in repeat tests. Much of this scatter was attributed to lubricant "breakdown" which will be discussed later in this report.

- Tests for no filter, 15 μm and 3 μm levels of filtration using 9310/9310 wear and employing lubricant 0-79-16 demonstrated good repeatability in average total wear between the two filtration levels. The no filter condition exhibited approximately 30 percent higher wear. Wear with no filtration gave very high deposits with a rating of 112 whereas the deposits for nonwear with no filtration was considerably lower with a rating of 32. Although the wear with both levels of filtration gave what appeared to be a significant effect of filtration on deposit mitigation, if the deposit rating means were adjusted for the effects of total wear there might not be a statistically significant difference. The difference between 15 μm and 3 μm filtration did not appear to be of much significance. The 3 μm filtration showed slight improvement of neutralization number over 15 μm filtration, but 3 μm filtration did not show that same improvement in viscosity change. In fact 3 μm filtration

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gave a larger increase in viscosity than nonwear-no filtration tests, thus showing questionable advantage for 3 μm filtration for this particular lubricant under these test conditions.

- Tests for no filter and 15 μm filtration, using both M-50/M-50 and silver/M-50 wear, and using lubricant O-79-17 were performed. Comparison of the averaged test results for the two combinations of wear materials and without and with 15 μm filtration were made. For M-50 steel wear only, there was less than half the wear for filtration than measured without filtration. Consequently, the averaged results were somewhat obscured and were left for comment after statistical analysis. On the other hand, it appeared that some improvement resulted in deposit formation and viscosity change with 15 μm filtration, but no improvement in NN change was apparent. Silver/M-50 wear showed a definite improvement in deposit rating for 15 μm filtration, with a slight improvement in NN change and no significant change in viscosity.

- Tests for no filter, 15 μm and 3 μm filtration with 9310/9310 wear and employing lubricant O-79-20 demonstrated good repeatability in average total wear for all three conditions. The 3 μm filtration condition had the highest wear of 0.79 g and the 15 μm and nonfiltration conditions had slightly lower wear of 0.77 g and 0.72 g, respectively. Wear with no filtration gave very high deposits with a rating of 119 whereas the deposits for wear with 15 μm and 3 μm filtration gave ratings of 96 and 89, respectively. Although the wear with both levels of filtration gave what appeared to be moderate mitigation effects on deposits, there was not a large difference between the 15 μm and 3 μm filtration. Comparing 15 μm with 3 μm filtration for 9310 steel wear with lubricant O-79-20 shows the 15 μm filters to be slightly superior to 3 μm filters for both viscosity increase and NN change.

- Tests for no filter and 15 μm filtration with 9310/9310 wear and using lubricant O-82-3 were performed. Comparison of the test

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results showed that these two conditions demonstrated good
repeatability. Wear with no filtration gave high deposits whereas
nonwear with no filtration gave very low deposits. There was some
mitigation of effects on deposit rating with 15 μm filtration.
Wear with or without filtration for this lubricant gave very
deleterious effects of both viscosity increase and neutralization
number and showed the vulnerability of employing this lubricant in
the presence of wear at temperatures simulative of the hot-wall
surface. On the other hand, it was shown that lower temperatures
with limited wear debris present, probably gives very good deposi-
tion and reasonable degradation results for this lubricant.

Statistical Analysis

The data to be analyzed in this study consisted of three response vari-
ables, namely:

- Deposit rating
- Viscosity increase at $40^{\circ}C$, %
- Neutralization number (NN) change, mg KOH/g

The test parameters included upper and lower coupon wear (in grams), coupon
material (none, M-50/M-50, 9310/9310, silver/M-50 and 4616/M-50), lubricant
formulation (eight), and filter size (none, 3 or 15 μm). The purpose of the
analysis was to determine if the test parameters had any effect on each of the
above response variables.

Initially the effects of filter size were ignored since this parameter
was not extensively explored. Tables 5 and 6 contain the means and standard
errors (i.e., standard deviations of the means) of the deposit rating, vis-
cosity, and neutralization number for each of the lubricants and coupon mat-
erials. These reflect the values obtained when no filter was present. Plots
of the relative frequency of the occurrence of these data generally were bell--
shaped although occasionally significant tailing was observed at one end of
the curves.

TABLE 5. LUBRICANT MEANS AND STANDARD ERRORS FOR DEPOSIT
RATING, VISCOSITY, AND NEUTRALIZATION NUMBER

Lubricant Code	Deposit		40°C Viscosity Increase, %		NN Change, mg KOH/g	
	Mean	Std Error	Mean	Std Error	Mean	Std Error
0-71-11	24.5	6.01	- 4.3	0.37	3.52	0.19
0-76-9	81.0	10.44	28.4	5.80	21.50	3.43
0-77-4	74.3	7.73	68.7	16.96	10.28	1.92
0-79-16	73.2	8.72	9.4	0.49	0.66	0.11
0-79-17	89.8	8.86	16.7	1.08	0.79	0.08
0-79-20	78.9	8.83	7.7	0.47	0.72	0.12
0-82-2	61.6	3.50	8.4	0.20	2.14	0.14
0-82-3	53.0	9.10	82.1	21.84	5.27	1.37
Significance	0.000	0.167	0.000	0.000	0.000	0.000

TABLE 6. COUPON MATERIAL MEANS AND STANDARD ERRORS FOR DEPOSIT
RATING, VISCOSITY, AND NEUTRALIZATION NUMBER

Coupon	Deposit		40°C Viscosity Increase, %		NN Change, mg KOH/g	
Material	Mean	Std Error	Mean	Std Error	Mean	Std Error
None	31.3	3.81	18.8	9.85	3.14	1.20
M-50/M-50	66.6	5.60	32.6	11.58	6.87	2.26
9310/9310	95.1	5.02	33.7	12.26	6.79	2.31
Silver/M-50	68.7	8.69	34.4	13.40	7.17	2.35
4616/M-50	73.6	6.39	25.0	8.64	5.73	2.06
Significance	0.000	0.086	0.831	0.401	0.637	0.113

Using a one-way analysis of variance (ANOVA) a simple statistical comparison can be made among the various means. This technique compares the mean values to see if any one is significantly different from all the others. The analysis determines whether the discrepancies between the various lubricant and material averages are greater than could reasonably be expected from the variation that occurs within these classifications. A measure of the probability of obtaining the averages that were observed, given one assumes no differences exist, is expressed as the probability level (p) of the test. A small probability (i.e., $p < .05$) indicates there are significant discrepancies in the average, while a large probability (i.e., $p > .05$) indicates no change. Since all the probabilities at the bottom of the mean columns in Table 5 are small, the data indicate that the means are significantly different among the lubricants for all three response variables. In Table 6, however, the data show that only the deposit rating averages differ significantly among the coupon materials, while no change is noted among the viscosity and neutralization number means.

The variances (i.e., squared standard error x sample size) for the data summarized in Tables 5 and 6 also were checked for equality. As indicated by the probability levels given at the bottom of the standard error columns in these tables, the variances for viscosity and neutralization number differed significantly among the lubricants, while all other variances showed no differences. Since equality of variances is an assumption in an ANOVA test, the tests for the equality of the viscosity and neutralization number averages among the lubricants were adjusted. Instead of using the common F statistic, a Brown-Forsythe[5] statistic was employed. The probability levels at the bottom of Table 5 for the above two variables are based on this modification.

The effects of wear on the coupon materials were examined at this stage to determine if they might change the above results. Since differing materials were used on the upper and lower coupons, both upper and lower wear values were examined. Figures 12-17 depict the plots of each of the three response variables against these two wear variables. Indicated on the plots by symbols are the performance of each coupon material. Several interesting results are evident from these graphs.

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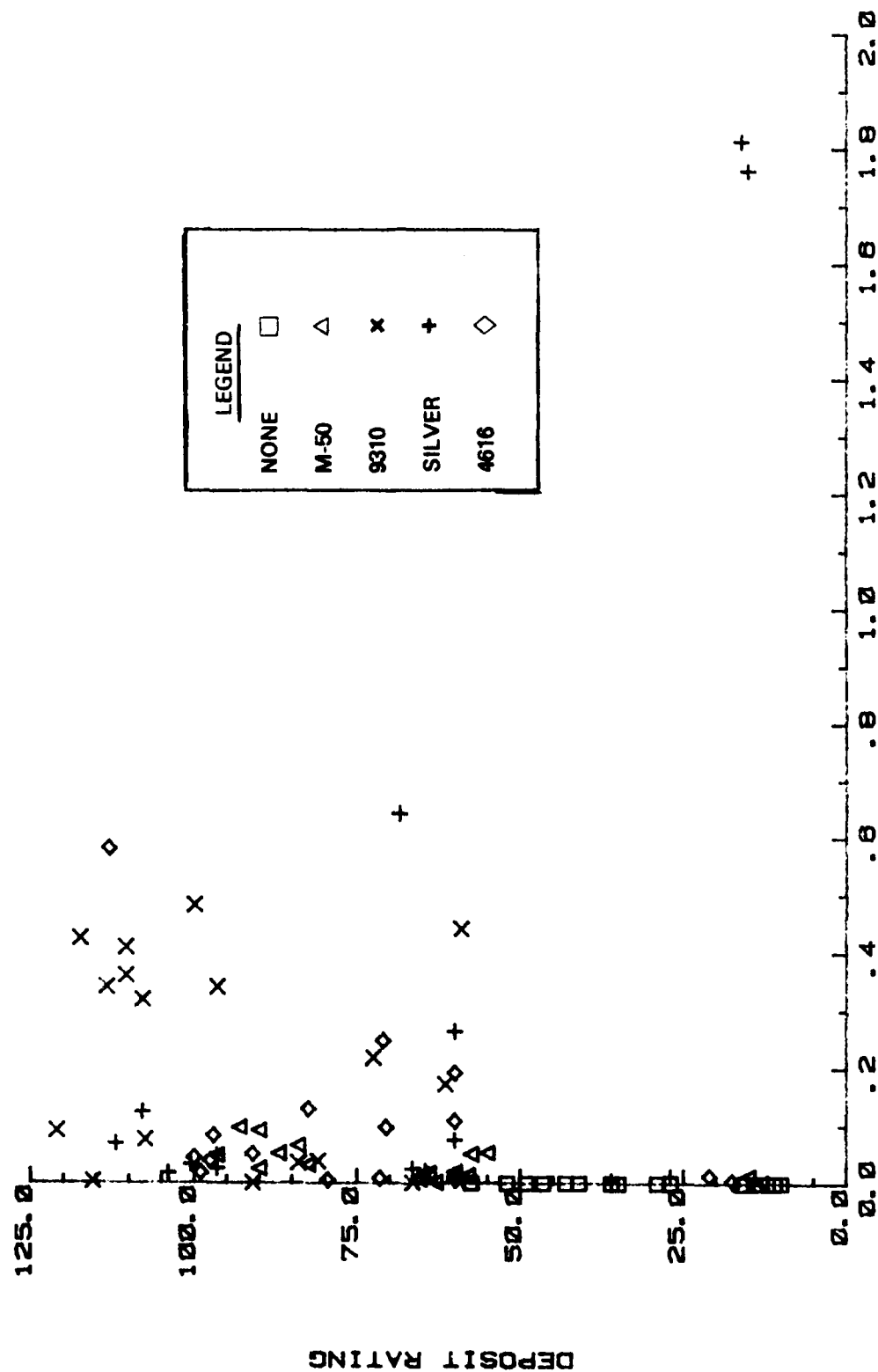
FIGURE   DEPOSITS FOR EIGHT LUBRICANTS VERSUS UPPER COUPON WEAR ONLY

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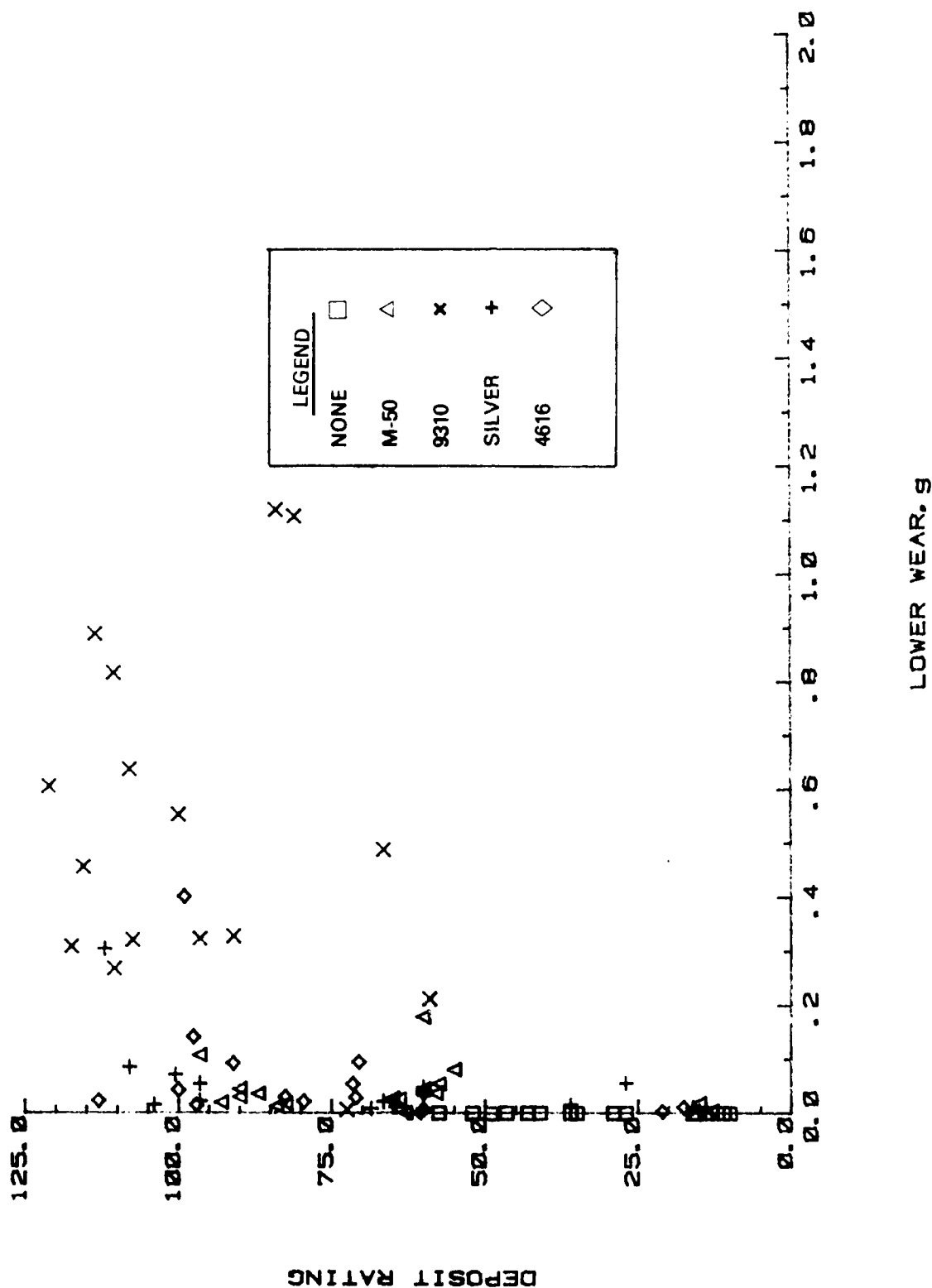
FIGURE 13. DEPOSITS FOR EIGHT LUBRICANTS VERSUS LOWER COUPON WEAR ONLY

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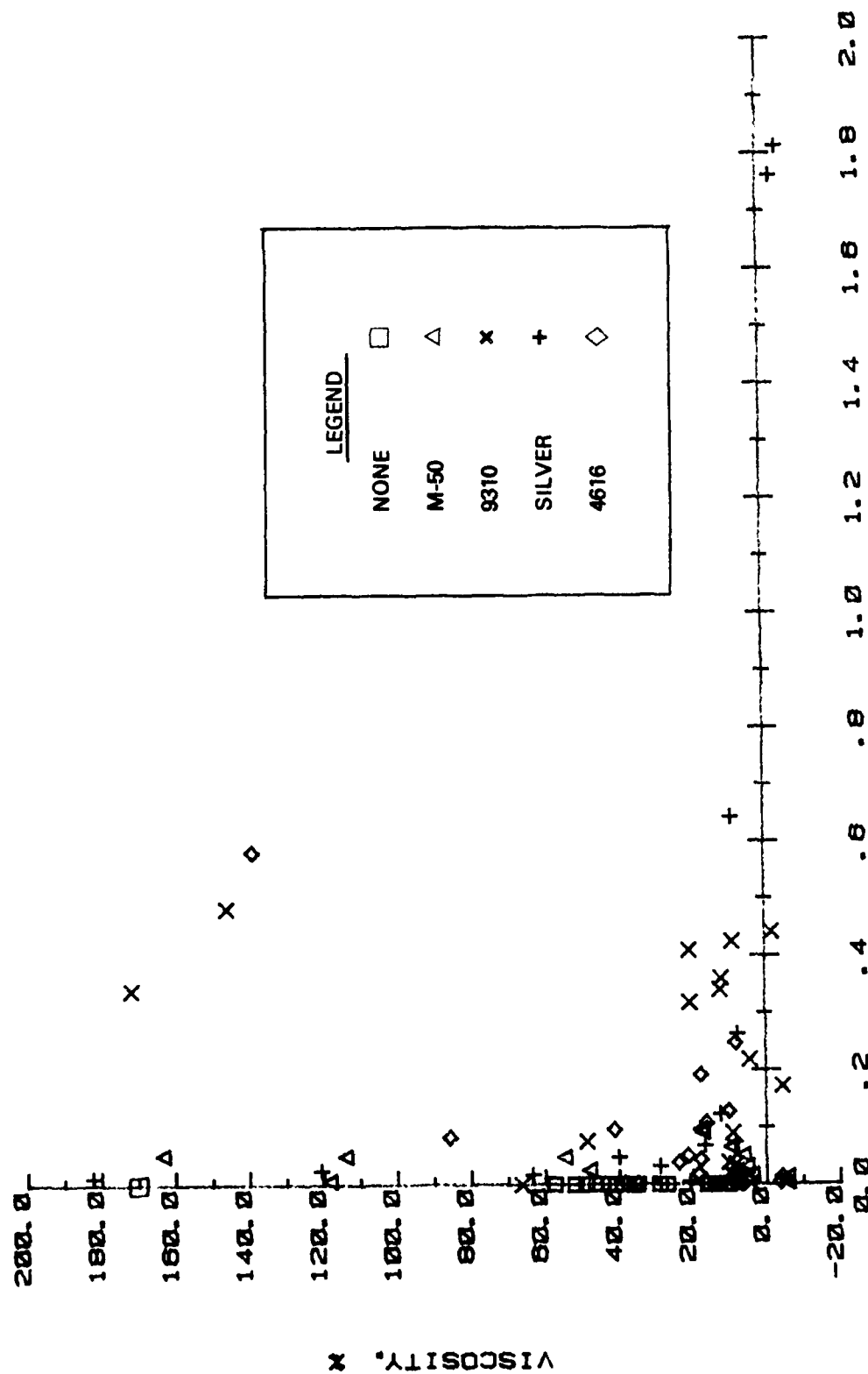
FIGURE 14. PERCENT VISCOSITY INCREASE FOR EIGHT LUBRICANTS VERSUS UPPER COUPON WEAR ONLY

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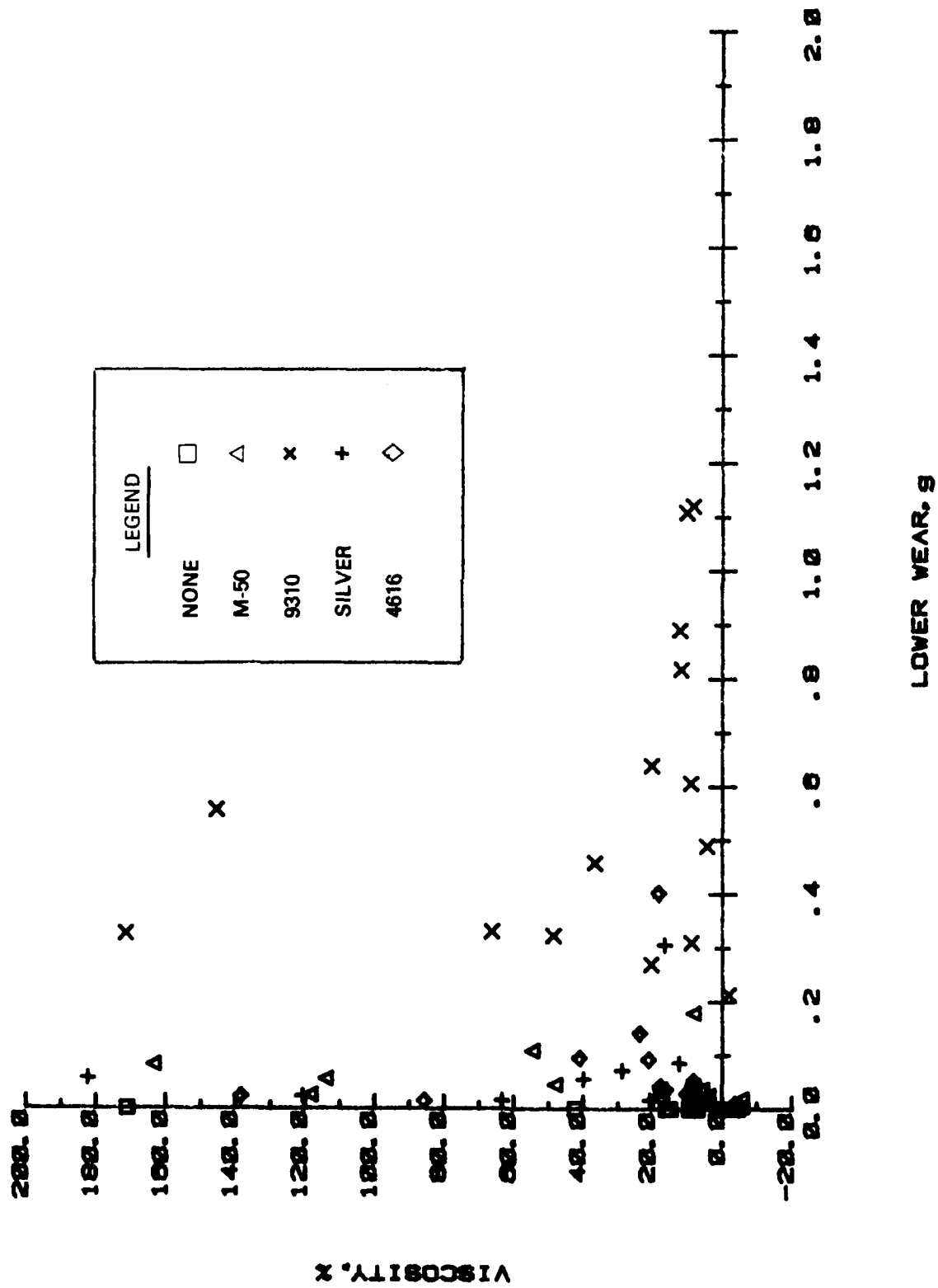
FIGURE 15. PERCENT VISCOSITY INCREASE FOR EIGHT LUBRICANTS VERSUS LOWER COUPON WEAR ONLY

FIGURE 16. NEUTRALIZATION NUMBER CHANGE FOR EIGHT LUBRICANTS VERSUS UPPER COUPON WEAR ONLY

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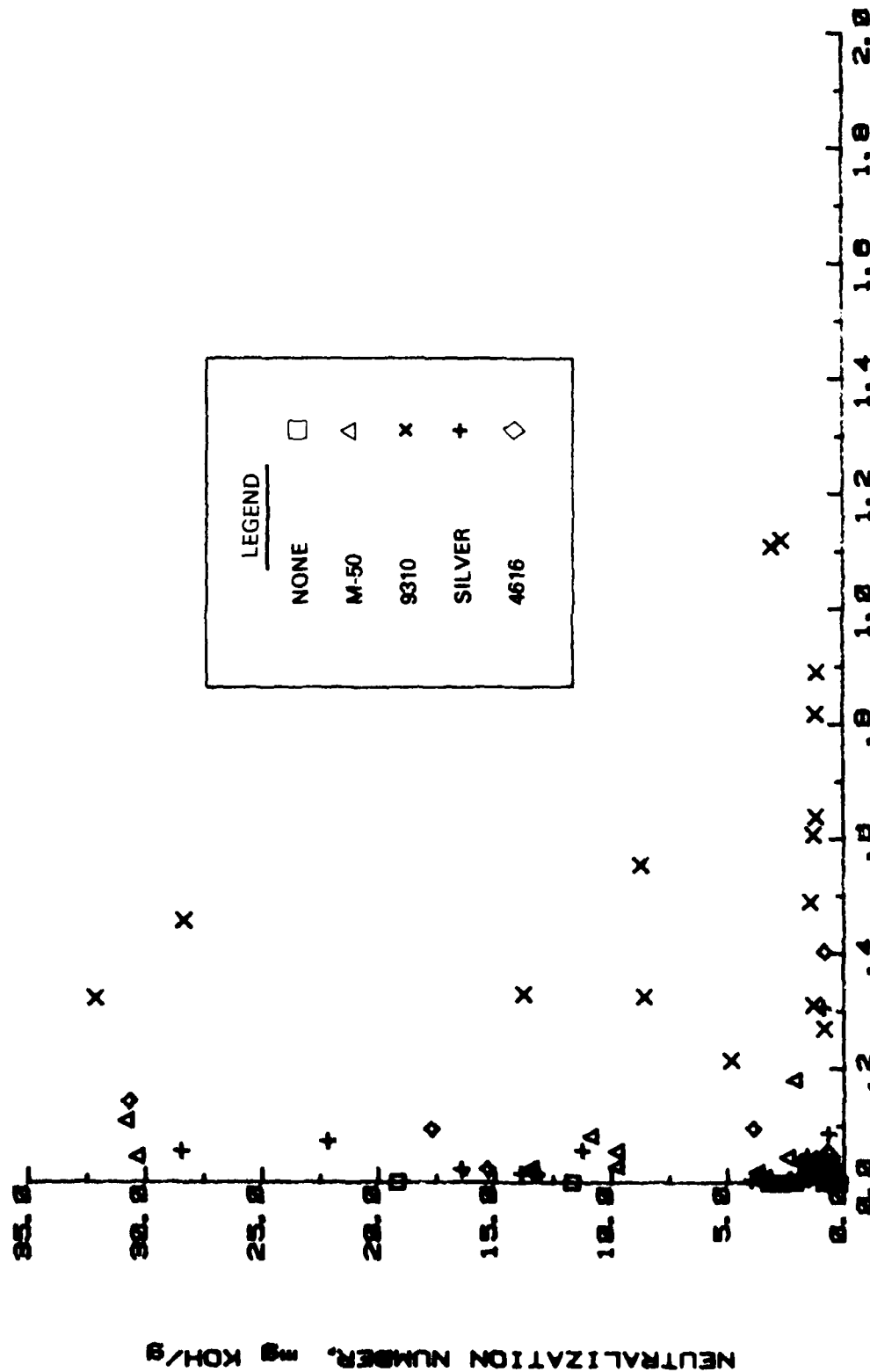
FIGURE 17. NEUTRALIZATION NUMBER CHANGE FOR EIGHT LUBRICANTS VERSUS LOWER COUPON WEAR ONLY

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Figures 12 and 13 display plots of deposit rating versus upper and lower wear. Clearly it appears that the deposit rating values increase greatly when the wear observations are nonzero. Further, the 9310 material tends to yield the largest deposit ratings (also see Table 5) while no material present gives the lowest ratings. In Figure 12 two of the silver upper wear points appear to be unusual in that they yield low deposit ratings but large wear values. This phenomenon suggests that the silver material may wear at a different rate than the other materials, with negligible effect on deposition.

Figures 14 and 15 depict the plots of viscosity versus both upper and lower wear. While these two plots are similar they are very different from those seen in Figures 12 and 13. Each material yields both large and small viscosity values so that, on the average, no one material dominates in viscosity. However, the viscosity values are lowest when no material is present. Again the two unusual upper wear values for silver are evident in the plots.

Figures 16 and 17 contain the plots of neutralization number versus the two wear variables. These plots are similar to those seen in Figures 14 and 15 for viscosity and similar conclusions result.

The above plots demonstrate that coupon wear appears to have some effect (though it may or may not be statistically significant) on the three response variables particularly in their relationship to the coupon material. The differences in wear among the materials can be seen by examining the upper and lower wear means and standard errors given in Table 7. As is indicated, the material means and variance are significantly different (using an ANOVA test) for both wear locations. Material 9310 has the largest lower wear mean but the second largest upper wear mean. The silver material has the largest upper wear mean; this result is due to the two unusual silver wear values observed in Figures 12, 14 and 16.

An adjustment for wear was made in the data analysis to account for the above wear effects. The statistical methodology chosen in achieving this objective was that of analysis of covariance. In this technique the averages of the three response variables (deposit rating, viscosity increase and NN change), at each of the 40 combinations of five materials and eight lubricants are adjusted for the effects of wear. The adjusted means then are compared

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TABLE 7. MATERIAL MEANS AND STANDARD ERRORS FOR
UPPER AND LOWER WEAR COUPONS

Wear Coupon	Upper Wear, g		Lower Wear, g	
Material	Mean	Standard Error	Mean	Standard Error
None	0.000	0.000	0.000	0.000
M-50	0.034	0.007	0.052	0.010
9310	0.220	0.043	0.497	0.081
Silver	0.328	0.159	-	-
4616	0.095	0.035	-	-
Significance	0.001	0.000	0.000	0.000

among themselves to determine if any are statistically different. Such an adjustment was made so that the response variable means are the best estimates of what they would have been if the wear had been the same for all material and lubricant combinations.

The adjustment for wear was made by attempting to fit a curve to the plots in Figures 12, 14 and 16 of each of the three response variables against the values of upper wear. Note that similar results would have been obtained if the lower wear observations had been utilized. For example, a fit would be made of the deposit rating as a function of upper wear using linear regression techniques. These fits were made for each of the combinations of material and lubricant types. The response variable means for the different upper wear values associated with them then were adjusted to what they would have been had they a common upper wear value.

This is illustrated for an idealized case in Figure 18 where the deposit rating averages for two material-lubricant combinations are fitted to straight lines as a function of the upper wear variable. For each material-lubricant group, variation in wear contributes to the variation in deposit rating. Hence, the distance between the two wear values, $\bar{W}_1$ and $\bar{W}_2$, affects the difference between the two corresponding deposit ratings, $\bar{D}_1$ and $\bar{D}_2$. If the deposit ratings had been observed from some common wear value, say W_0, then they would be comparable. Thus, the need for adjusting the deposit rating means is apparent. This is shown on the graph in the large discrepancy between the observed and adjusted deposit rating means.

Various curves fit to the data in Figures 12, 14 and 16 included straight line, logarithmic, exponential, power, and inverse. None of these fits, however, was statistically significant, although several indicated the stronger influence of wear on deposit rating as compared to the effect of wear on viscosity and neutralization number. A final attempted fit involved the use of an indicator wear variable, which had the value 0 for no wear and the value 1 with wear. When this variable was utilized, wear was shown to have a statistically significant effect on all three response variables. However, the adjustments were so large that several deposit rating means became negative. Due to such meaningless results, this final adjustment was not used and it
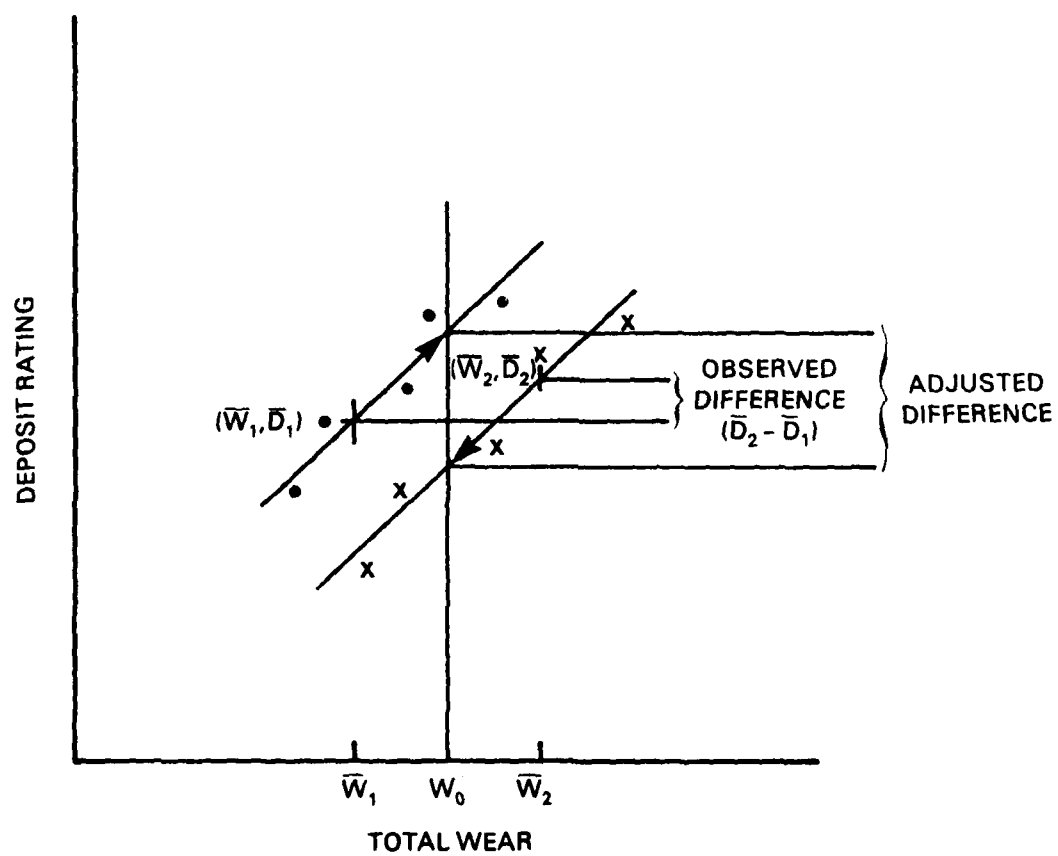
FIGURE 18. IDEALIZED EXAMPLE OF ADJUSTMENT OF DEPOSIT RATING MEANS

was decided to perform all the analyses using the unadjusted data and ignoring any wear magnitude effects. The statistical technique utilized was analysis of variance whereby the mean values of each test parameter are compared among themselves.

Table 8 consists of a summary of the results of the analysis of variance using deposit rating as the response variable. The sources of variation consist of material differences (M), lubricant differences (L), lubricant-material interactions (LxM), and the experimental error. The fifth column, labeled F, contains the value of the F test statistic for determining whether or not a given source of variation is influential. The last column, labeled p, gives the significance of the corresponding test statistic. A low p value, say <.05, indicates that there is a very small error (e.g., <5 percent) in concluding that the deposit rating means, across the combinations of the given source of variability, are statistically different. A large p value, say >.05, indicates that the deposit rating means are not statistically different for the given source of variation.

Analyzing Table 8, it can be seen that all sources of variability are significant. Material and lubricant types all have a significant influence (p<.001) on the mean deposit ratings. Also, there is a significant interaction among lubricants and materials.

Figure 19 contains a plot of the deposit rating means by lubricant and material. Each mean has associated with it a 95 percent confidence interval. These are illustrated by the enclosed vertical lines. The center of the line (plotted data point) is the mean while the end bars indicate the 95 percent confidence interval for each individual lubricant and material type.

The lowest deposit rating average occurs with lubricants O-82-3, O-76-9 and O-71-11 when no material is present. Similar low values occur with lubricant O-71-11 for all materials except 9310. The highest average occurs with lubricant O-79-20 and material 9310, and high deposit ratings occur with all materials for lubricants O-79-17 and O-76-9. There is clearly a significant difference between the deposit rating averages when no material is present, and material 9310 has a higher average than all the other materials. Other conclusions of this type can be drawn by carefully observing Figure 19.

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TABLE 8. ANALYSIS OF VARIANCE FOR DEPOSIT RATING

Source	Degrees of Freedom	Sum of Squares	Mean Square	F	p
Material (M)	4	37973.6	9493.4	243.70	0.000
Lubricant (L)	7	29954.3	4279.2	109.85	0.000
LxM	28	15807.6	564.6	14.49	0.000
Error	43	1714.0	39.0		
Total	83				
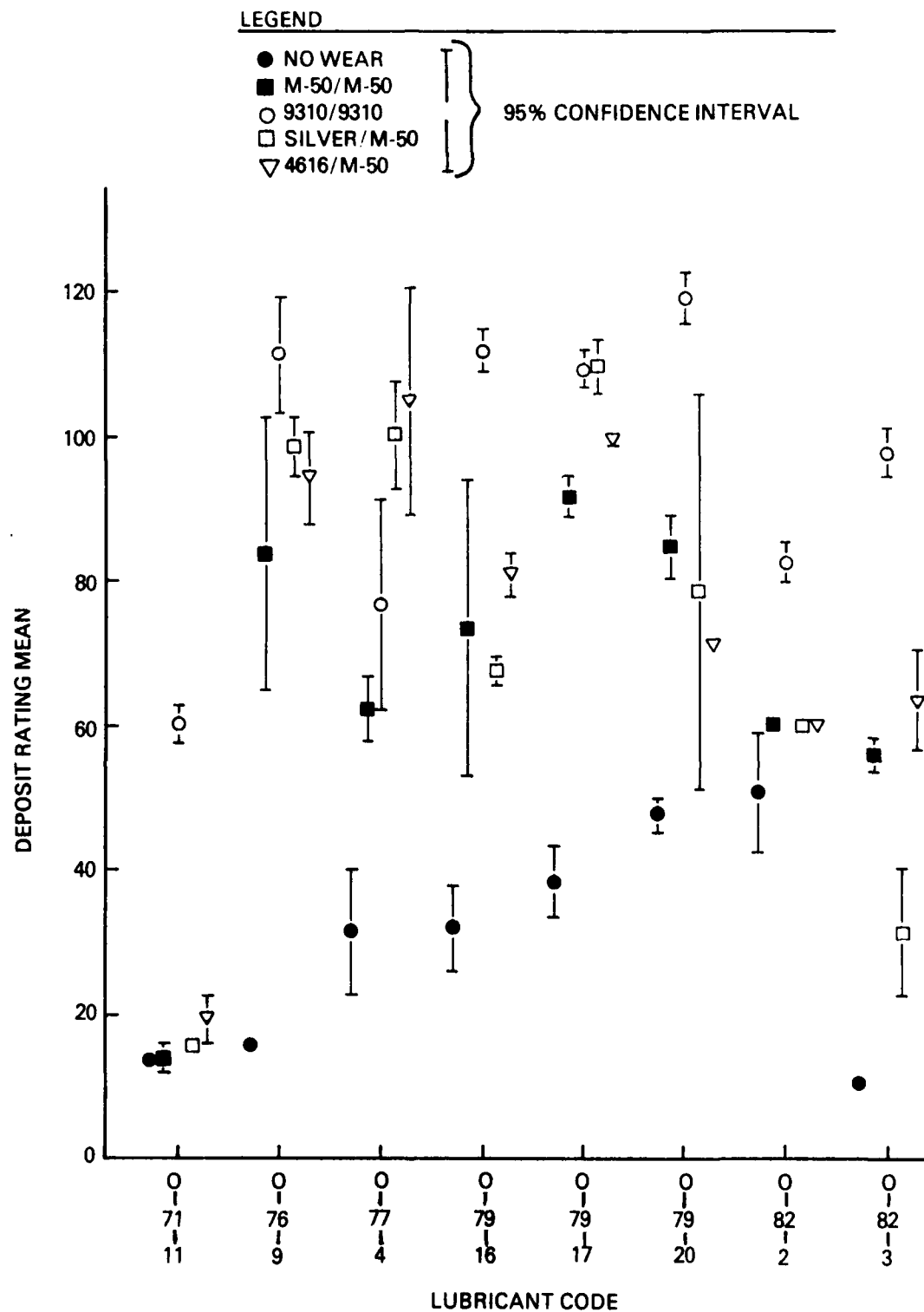
FIGURE 19. DEPOSIT RATING MEANS VERSUS LUBRICANT AND WEAR MATERIAL

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Tables 9 and 10 contain the analysis of variance results using viscosity increase and neutralization number change. From the F statistics in column 5 and the p values in column 6, it can be seen that a significant interaction exists between lubricant and material. However, while the lubricant main effect is significant, the material means do not differ significantly.

Figures 20 and 21 display plots of the viscosity and NN means versus lubricant and material. As in Figure 19 each mean has associated with it a 95 percent confidence interval. For viscosity, lubricant 0-82-3 with material 9310 had the highest mean, while all combinations of materials and lubricant 0-71-11 had the lowest means. Overall, taken separately, lubricants 0-82-3 and 0-77-4 had the largest viscosity averages while lubricant 0-71-11 yielded the lowest average. The lowest viscosity average for materials occurred when none was present. Other conclusions on viscosity can be gained by examining Tables 5 and 6 and Figure 20.

In Figure 21 the highest NN mean occurs with lubricant 0-76-9 and material 9310 while there are several combinations of materials and lubricants that yield low averages. Taken separately, lubricant 0-76-9 has the highest overall NN mean followed by lubricant 0-77-4. No single material is dominant and this explains the lack of a significant material effect in Table 10.

All of the previous results pertain to the condition when no filter was present in the test system. To evaluate the filter effect consider Table 11 which contains a list of the lubricant and material combinations where filters were utilized. A total of 30 observations were taken including 12 with no filters, 5 with 3 µm filters, and 13 with 15 µm filters.

Given the limited combinations listed in Table 11 it is not possible to evaluate statistically the effects of filtering on all the lubricants and materials. Table 12, however, contains the means of the three response variables for each of the listed combinations. Ignoring lubricant and material effects, it appears that the deposit rating means are higher when no filter is present as compared to when there is a filter. For the viscosity averages, the 3 µm filter yields a lower value than the other two cases. No filter differences are apparent when analyzing the NN means.

TABLE 9. ANALYSIS OF VARIANCE FOR VISCOSITY INCREASE

Source	Degrees of Freedom	Sum of Squares	Mean Square	F	p
Material (M)	4	2543.9	636.0	0.72	0.583
Lubricant (L)	7	86940.3	12420.0	14.07	0.000
LxM	28	53039.0	1894.3	2.15	0.011
Error	43	38852.9	883.0		
Total	83				

TABLE 10. ANALYSIS OF VARIANCE FOR NEUTRALIZATION NUMBER CHANGE

Source	Degrees of Freedom	Sum of Squares	Mean Square	F	p
Material (M)	4	144.1	36.0	2.33	0.071
Lubricant (L)	7	3832.1	547.4	35.38	0.000
LxM	28	1188.3	42.4	2.74	0.001
Error	43	680.8	15.5		
Total	83				
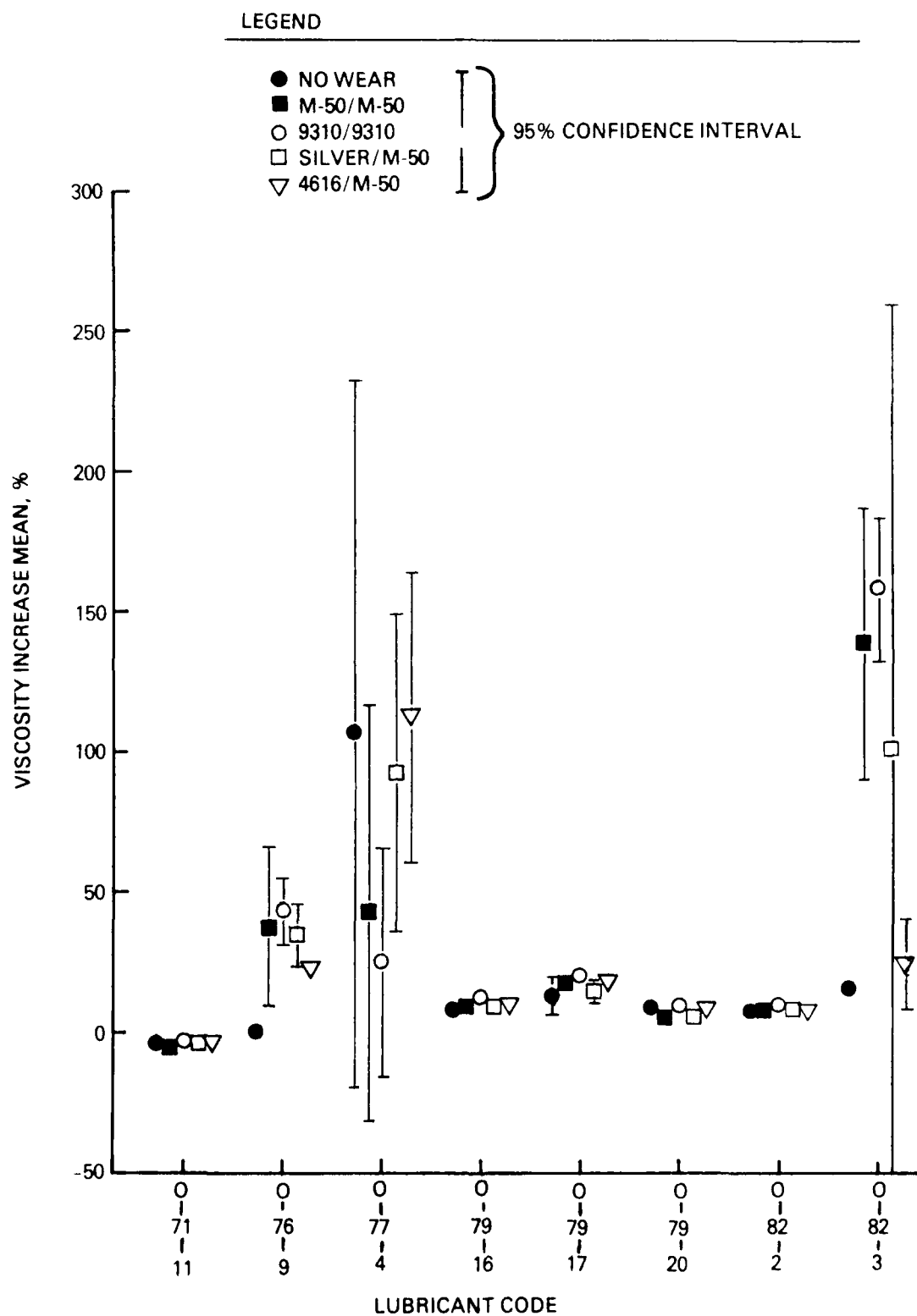
FIGURE 20. VISCOSITY MEANS VERSUS LUBRICANT AND WEAR MATERIAL
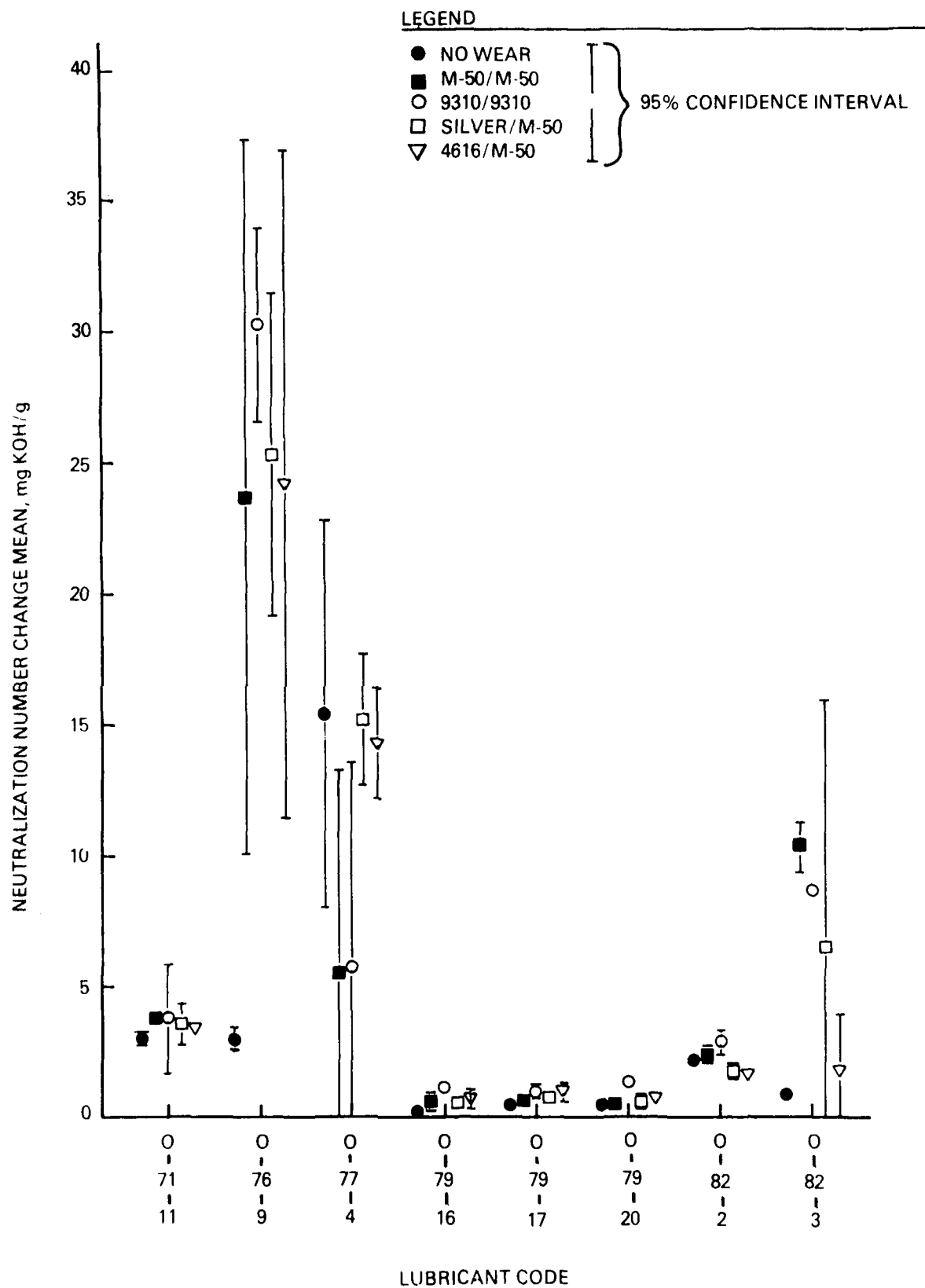
FIGURE 21. NEUTRALIZATION NUMBER MEAN VERSUS LUBRICANT AND WEAR MATERIAL

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TABLE 11. NUMBER OF OBSERVATIONS ON LUBRICANT-MATERIAL-FILTER
COMBINATIONS

Lubricant Code	Coupon Material	Filter		
		None	3μm	15μm
0-77-4	4616/M-50	2	1	3
0-79-16	9310/9310	2	2	2
0-79-17	M-50/M-50	2	0	2
0-79-17	Silver/M-50	2	0	2
0-79-20	9310/9310	2	2	2
0-82-3	9310/9310	2	0	2
	Totals	12	5	13

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TABLE 12. MEANS OF DEPOSIT RATING, PERCENT VISCOSITY INCREASE, AND
NEUTRALIZATION NUMBER CHANGE FOR LUBRICANT-MATERIAL-FILTER COMBINATIONS

Lubricant Code	Coupon Material	Response Variable								
		Deposit Rating			% Viscosity Increase			NN Change		
		None	3µm	15µm	None	3µm	15µm	None	3µm	15µm
0-77-4	4616/M-50	105.0	84.5	84.3	112.0	60.2	101.4	14.3	12.9	20.7
0-79-16	9310/9310	112.0	89.0	90.0	12.0	9.0	6.3	1.2	0.4	0.6
0-79-17	M-50/M-50	91.5	-	72.5	17.6	-	13.8	0.6	-	0.6
0-79-17	Silver/ M-50	110.0	-	47.0	14.5	-	14.5	0.8	-	0.7
0-79-20	9310/9310	119.3	89.0	96.0	9.0	9.1	8.1	1.3	0.9	0.6
0-82-3	9310/9310	98.3	-	69.8	158.5	-	77.8	8.7	-	7.6
	Average	106.0	88.1	77.2	53.9	19.3	41.9	4.5	3.1	6.3

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An analysis of variance for each of the response variables was run using the five lubricants given in Table 11 and two filter conditions (i.e., present or absent). The material differences were not considered since a balanced design was not attainable. The results are contained in Table 13. As expected, there were significant differences among the means for the five lubricants on all three response variables. There also were significant differences between the two filter means for deposit rating and viscosity but no differences existed between the filter means for NN change. This confirms the results noted from the examination of the means given in Table 12.

Lubricant Wear-Metal Analyses

Atomic Absorption Spectrophotometer (AA). Lubricant samples that were collected during wear tests (with and without filtration) were analyzed for trace amounts of either/and iron (Fe), copper (Cu) and silver (Ag) by AA. AA was employed instead of X-ray fluorescence for these analyses because it will determine concentrations below 10 ppm down to less than 1 ppm of these particular metals.

Figure 22 shows average Fe values for all of the nonfiltration M-50/ M-50 steel wear tests for each of the eight lubricants. Also, documented in the figure immediately following the lubricant code is the average total coupon wear that was measured after testing of each lubricant. As seen there seems to be no correlation between this total coupon wear and the trace-metal amounts as measured by AA. It is interesting that two lubricants, 0-76-9 and 0-82-3 continued to increase in trace iron throughout the tests while the other lubricants tended to reach a maximum at about 16-24 hr and level off or decrease for the remainder of testing. Figure 23 shows a similar plot for 9310/9310 steel wear tests. As shown lubricant 0-82-3 and 0-76-9 behaved somewhat similarly in Fe content. On the other hand, 0-82-2 behaved quite differently than it did for M-50/M-50 wear. Regardless, it can be said that the overall general trend was much the same even though average total coupon wear for 9310/9310 wear was approximately nine times the amount realized with M-50/M-50 wear. The trace iron measurements for 9310/9310 wear were of the order of two to three times that determined for M-50/M-50 wear.

TABLE 13. ANALYSIS OF VARIANCE FOR DEPOSIT RATING, PERCENT
VISCOSITY INCREASE, AND NEUTRALIZATION NUMBER CHANGE--FILTER EFFECTS

Source		Degrees of Freedom	Sum of Squares	Mean Square	F	p
			Deposit Rating			
Filter	(F)	1	5180.1	5180.1	34.99	.000
Lubricant	(L)	4	2831.2	707.8	4.78	.007
FxL		4	444.8	111.2	0.75	.569
Error		20	2961.1	148.1		
			% Viscosity Increase			
Filter	(F)	1	3119.0	3119.0	8.12	.010
Lubricant	(L)	4	59181.5	14795.4	38.53	.000
FxL		4	5110.1	1277.5	3.33	.030
Error		20	7679.5	384.0		
			NN Change			
Filter	(F)	1	1.2	1.2	0.08	.784
Lubricant	(L)	4	1066.5	266.6	17.42	.000
FxL		4	27.3	6.8	0.45	.775
Error		20	306.1	15.3		

NO FILTRATION
M-50/M-50 WEAR COUPON

| Lubricant Coupon Code	Avg Coupon Wear, g
0-82-3	0.12
0-76-9	0.09
0-79-17	0.12
0-77-4	0.04
0-79-16	0.02
0-79-20	0.07
0-82-2	0.13
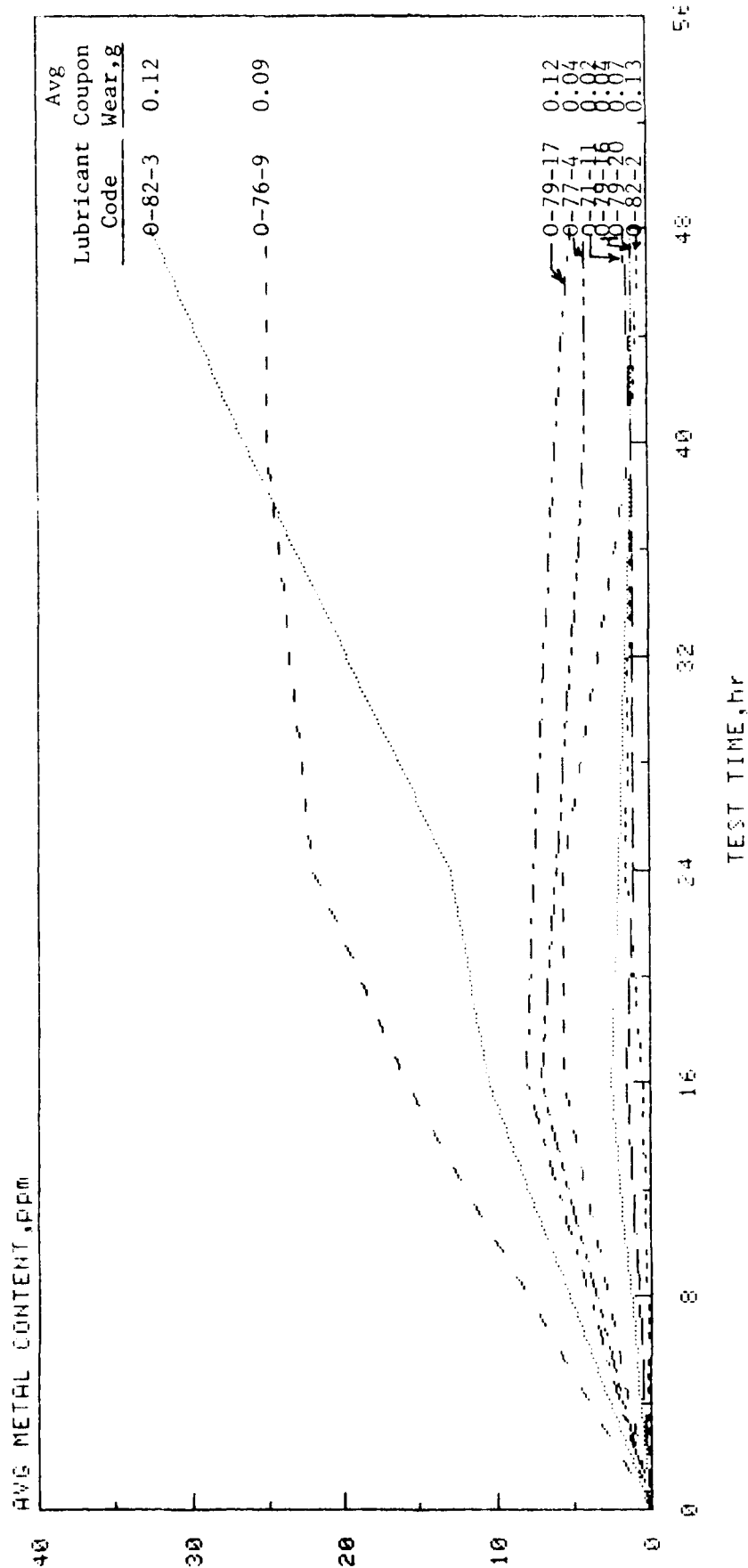
FIGURE 22. AVERAGE IRON CONTENTS FOR EIGHT LUBRICANTS DURING WEAR TESTS--M-50/M-50 WEAR COUPONS
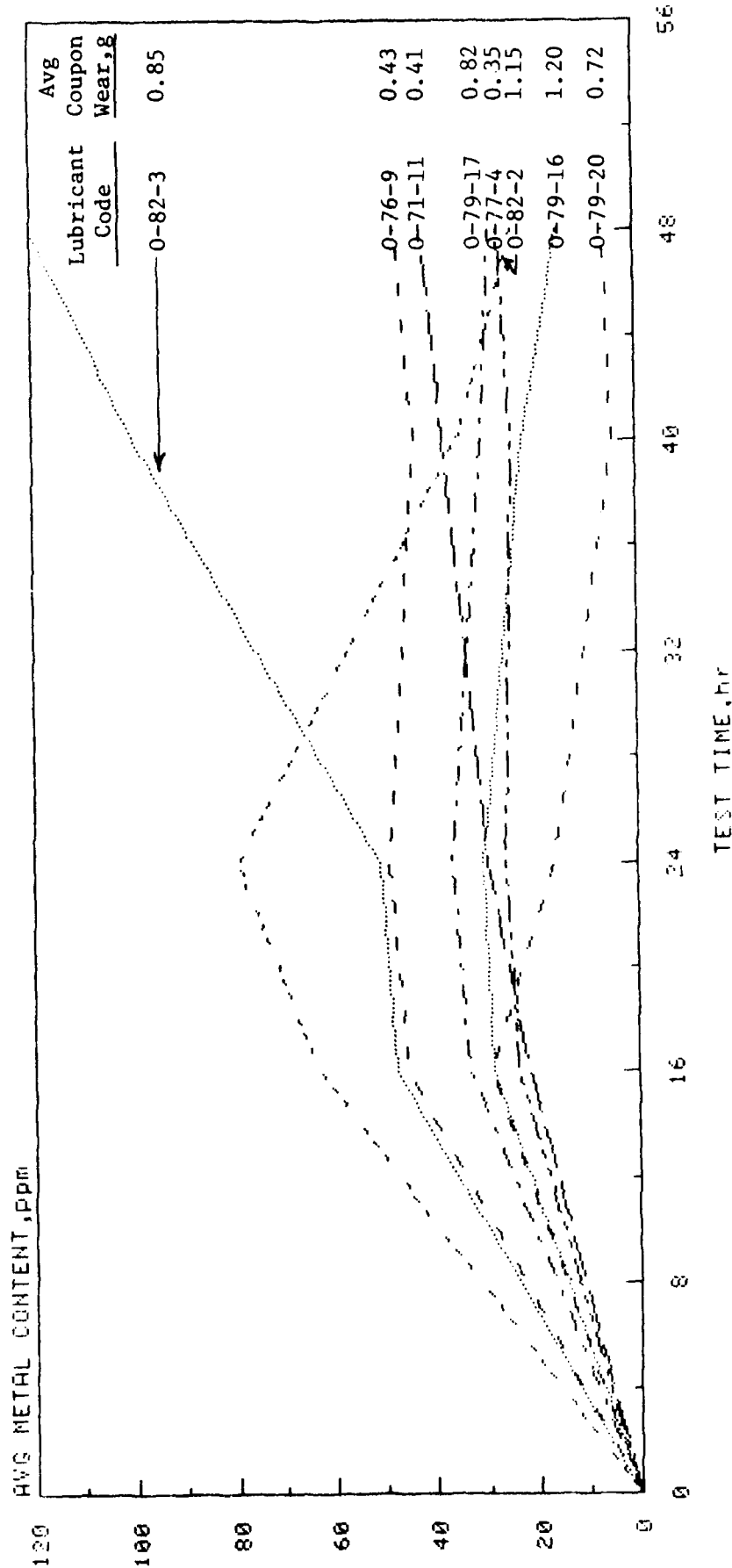
FIGURE 23. AVERAGE IRON CONTENTS FOR EIGHT LUBRICANTS
DURING WEAR TESTS—9310/9310 WEAR COUPONS

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Figure 24 shows average Cu and Fe contents in lubricant 0-77-4 samples during wear testing. As seen, for the first 24 hr of testing all of the samples showed relatively low amounts of wear metals. After that, until the end of the test (48 hr), the 3 μm filters maintained a relatively constant amount of Cu and Fe particles of approximately 7 and 1 ppm, respectively. For both metals the 15 μm filters showed wear metals approximately three times as great. The without-filtration samples showed considerably more Cu and Fe with maximum values of approximately 34 and 9, respectively, at the end of the test. There was not sufficient difference between wear metals in the before filter (upstream) and after filter (downstream) samples for this or any of the other lubricants. This suggests that there are many small particles of metals in the lubricant system that are in suspension and passing conveniently through the filters. Figure 25 shows average Fe contents in lubricant 0-79-16 samples during 9310/9310 wear testing. For this lubricant there was no significant difference between 15 μm and 3 μm filtration, before and after filter. Without filtration showed an increase in Fe for the first 24 hr with significant decrease thereafter to the end of the test. This indicates that the coupon wear was probably greatest during the first part of the test and/or much of the wear debris was continually falling to the bottom of the lubricant sump and not being circulated throughout the system. Figures 26 and 27 show a slight advantage in removing iron wear metals from lubricant 0-79-17. On the other hand, no advantage was shown in removing Ag wear particles. This indicates that 0-79-17 is not as susceptible to micronic filtration as some of the other lubricants tested, as far as wear-metal removal is concerned. Figure 28 showing averaged iron contents during lubricant 0-79-20 testing shows no advantage of 3 μm filtration over 15 μm filtration. Early in the test, filtration (either 15 μm or 3 μm) showed considerable improvement over nonfiltration, but this was not so for the last 8 hr (40-48 hr) of testing. Contrary to this, and shown in Figure 29, lubricant 0-82-3 displayed considerable improvement throughout the test for 15 μm filtration over nonfiltration. It is of interest that from 24 hr until the end of test both filtration and nonfiltration displayed a constant increase in Fe.
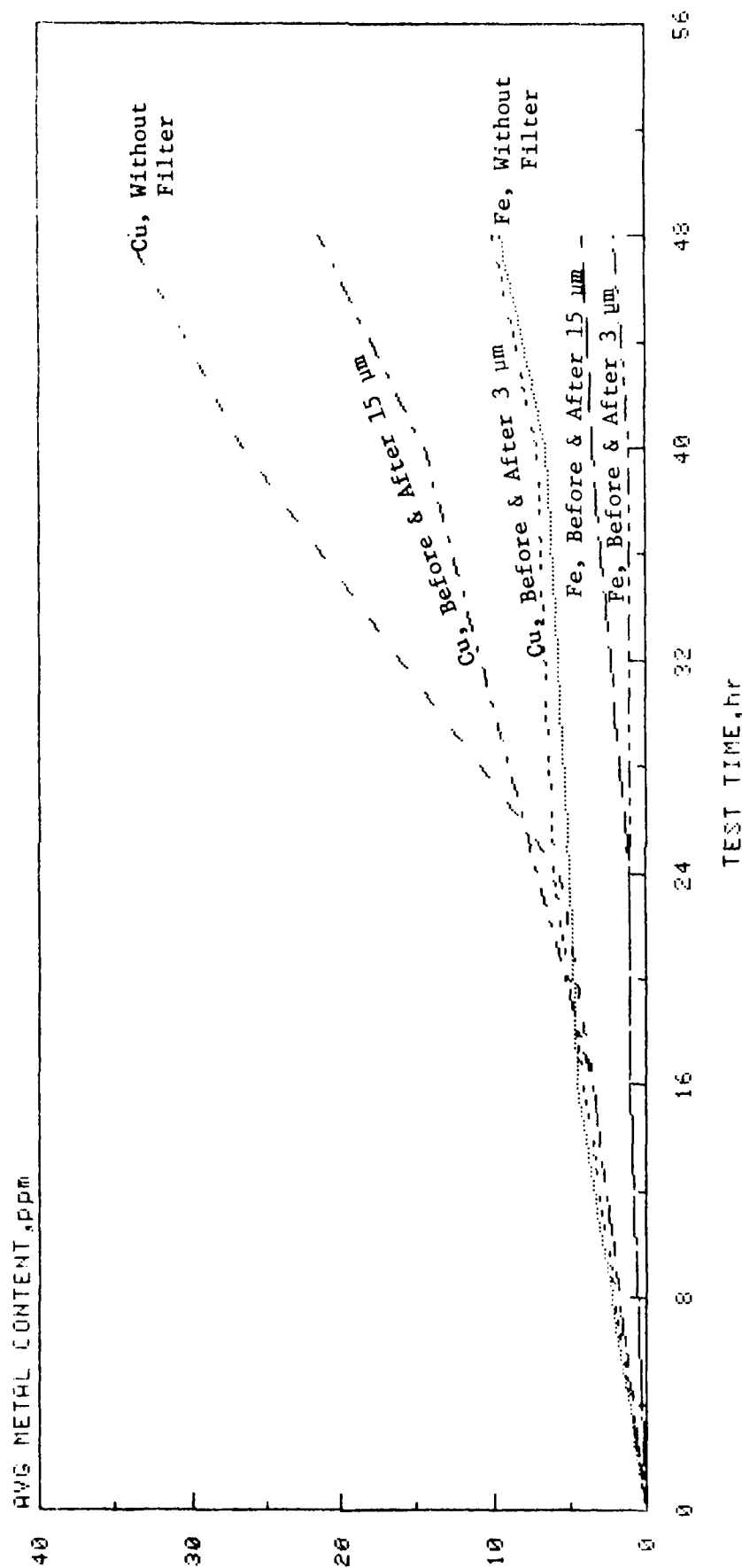
FIGURE 24. AVERAGE METAL CONTENTS DURING WEAR TESTS WITH
AND WITHOUT FILTRATION
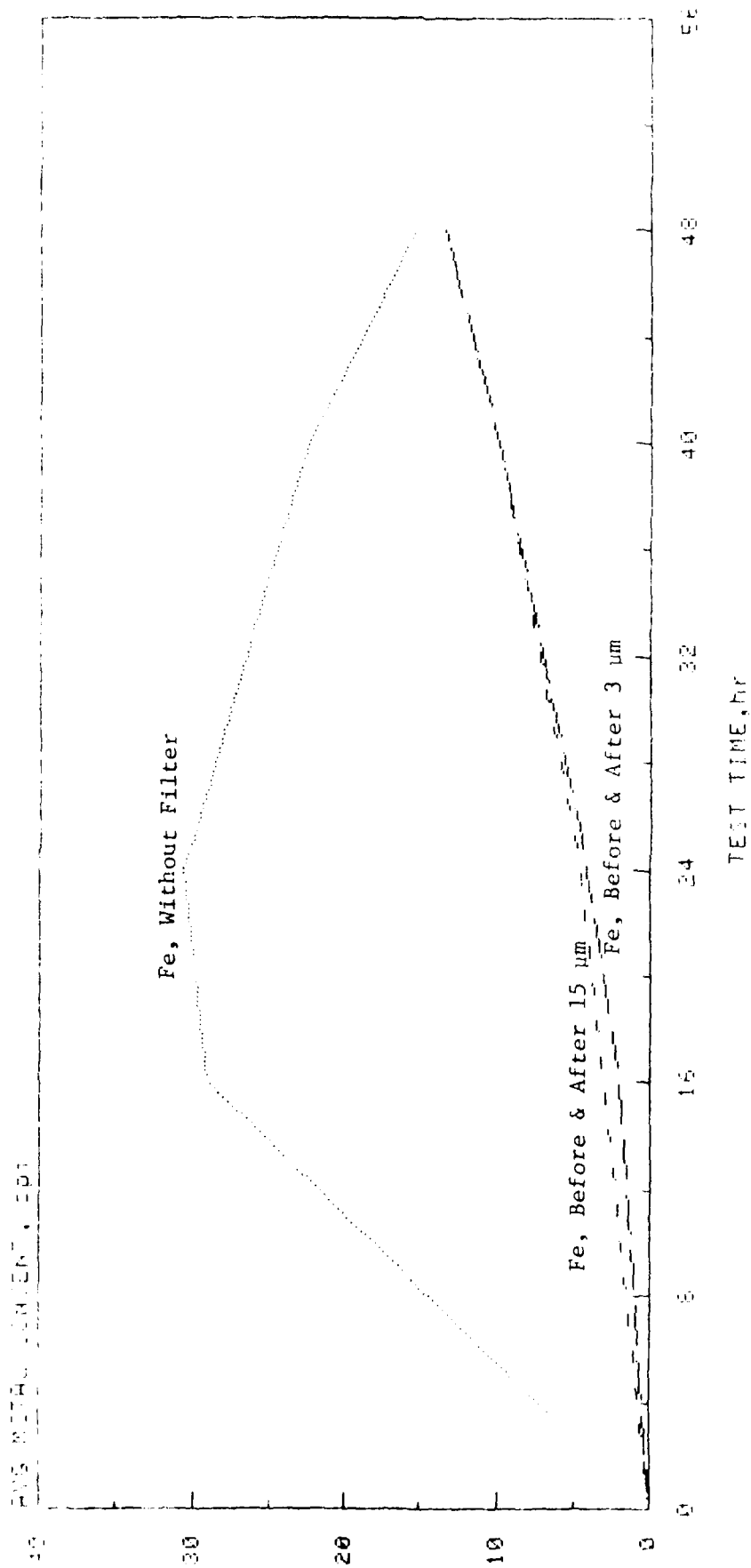
FIGURE 25.   AVERAGE IRON CONTENTS DURING WEAR TESTS
WITH LUBRICANT O-79-16
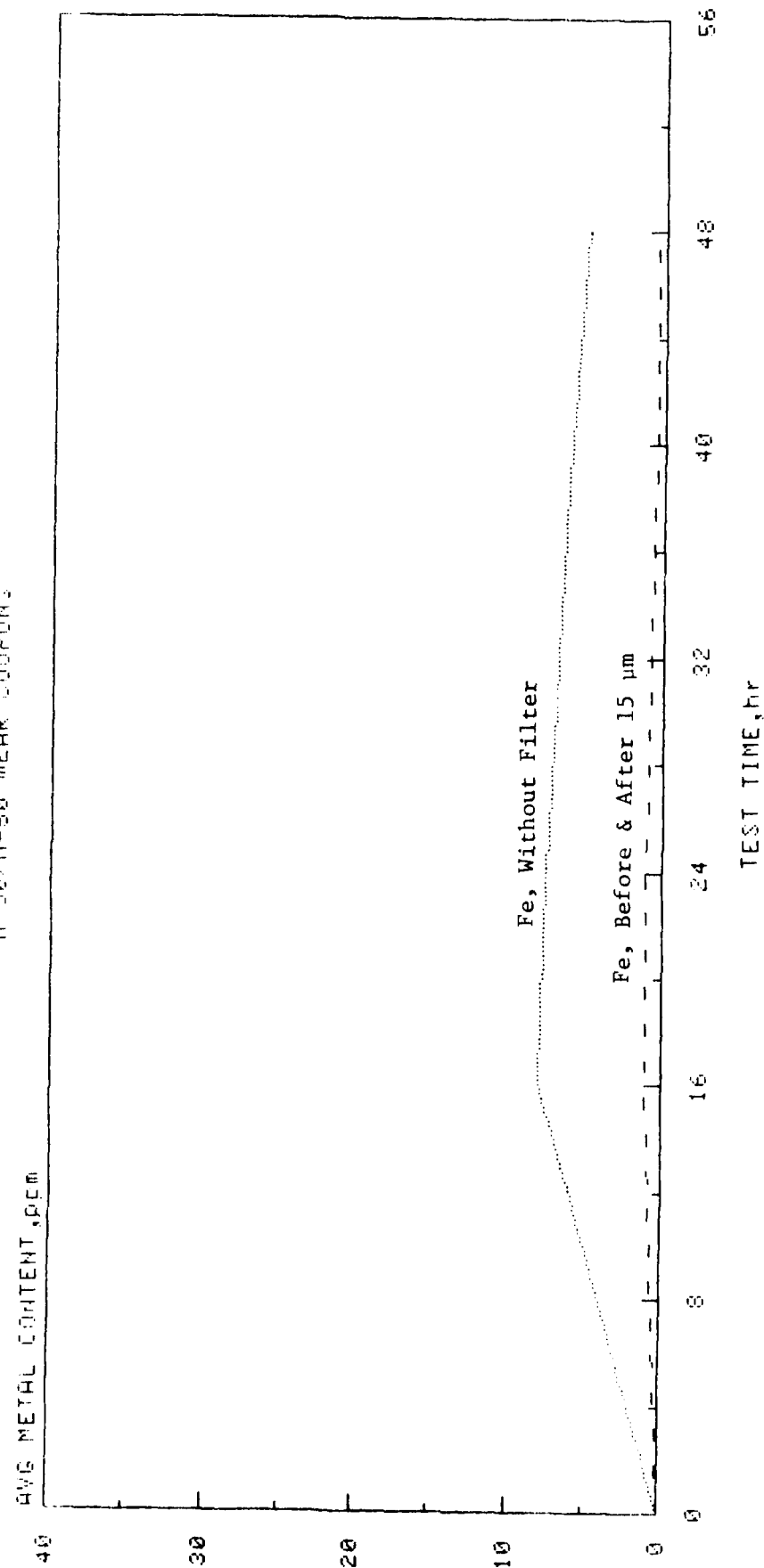
FIGURE 26. AVERAGE IRON CONTENTS DURING WEAR TESTS
WITH LUBRICANT O-79-17

LUBRICANT O-79-17

SILVER M-50 WEAR COUPONS

AVG METAL CONTENT, ppm

Fe, Without Filter

Ag, Without Filter—Fe & AC, Before & After 15 µm

TEST TIME, hr
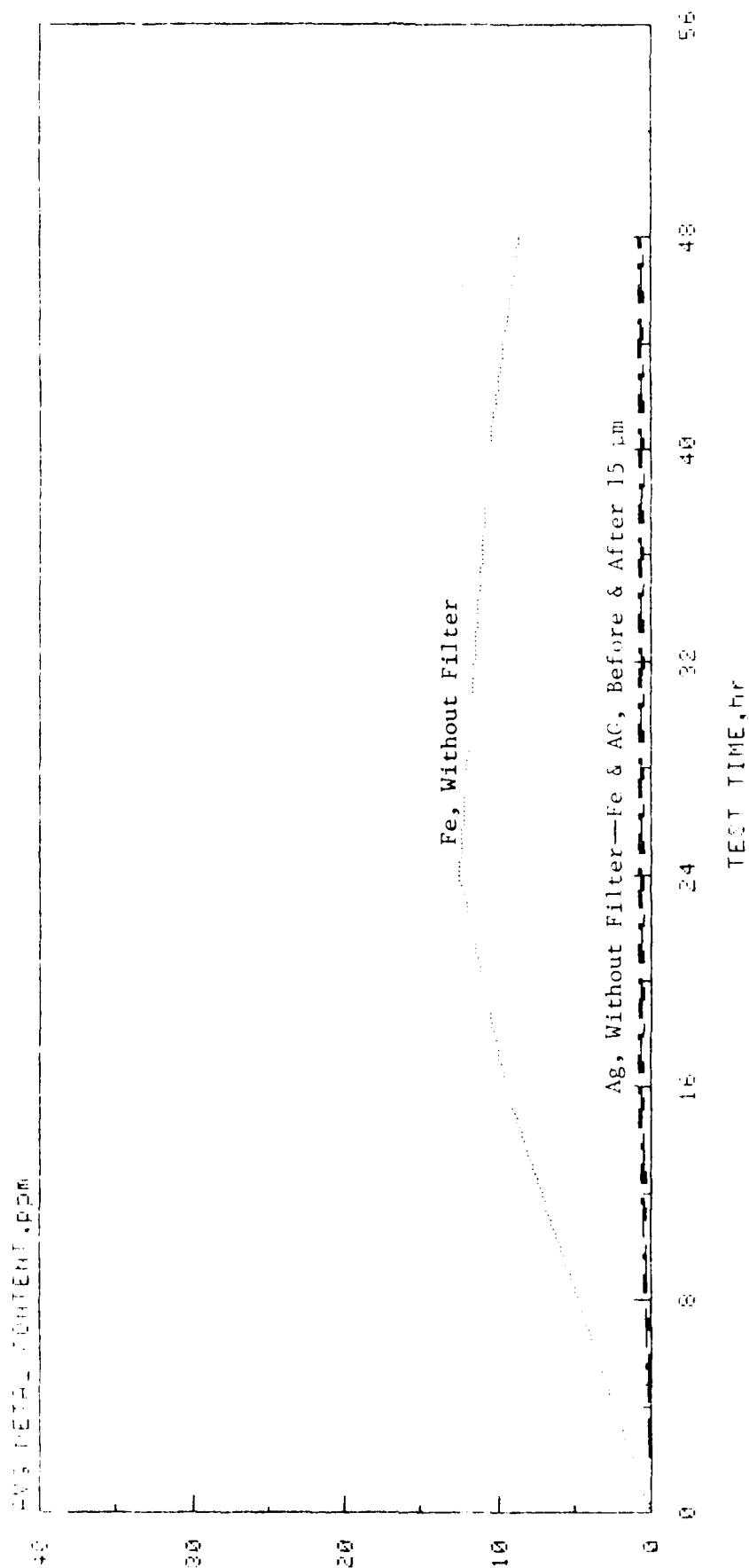
FIGURE 27. AVERAGE METAL CONTENTS DURING WEAR TESTS
WITH LUBRICANT O-79-17
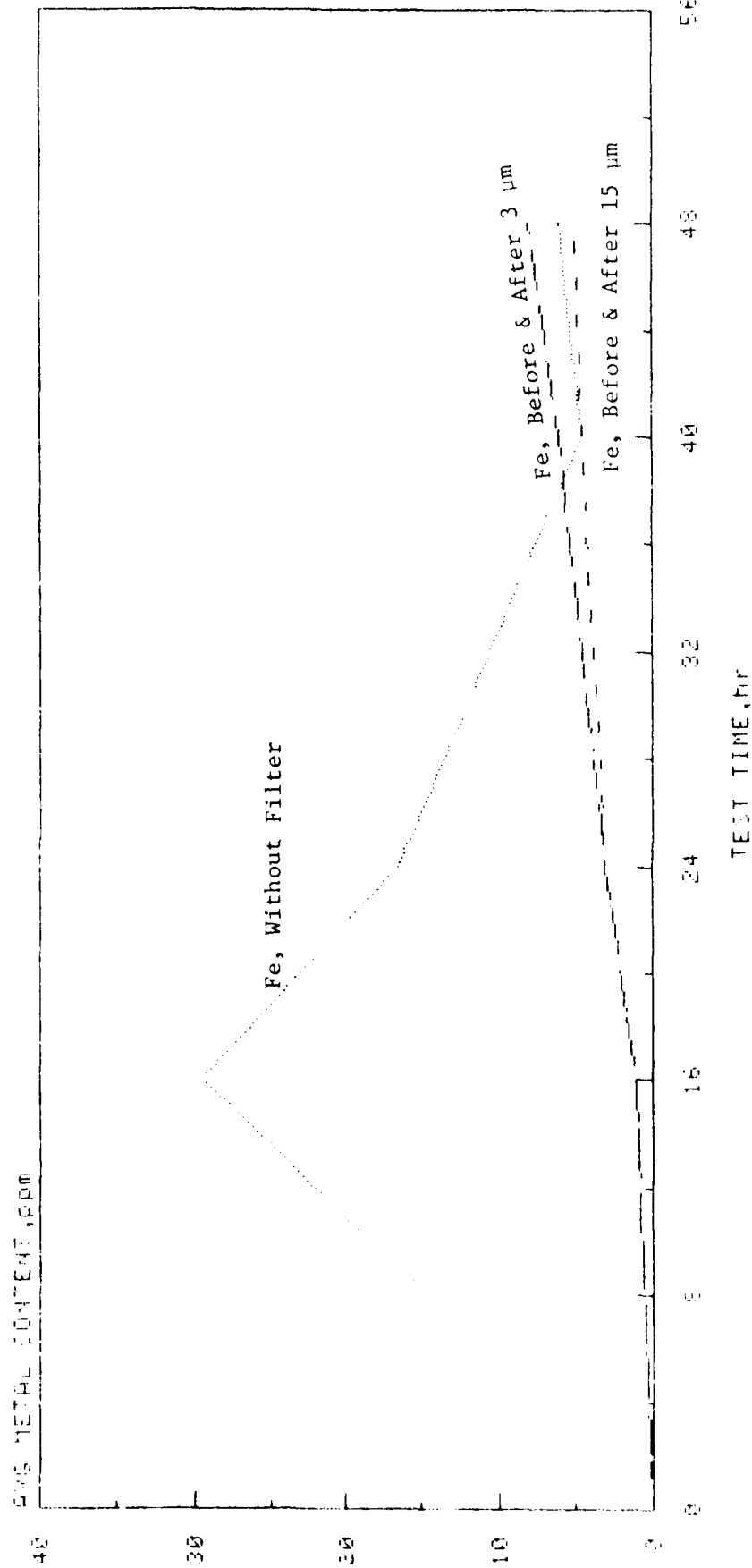
FIGURE 28. AVERAGE IRON CONTENTS DURING WEAR TESTS
WITH LUBRICANT O-79-20
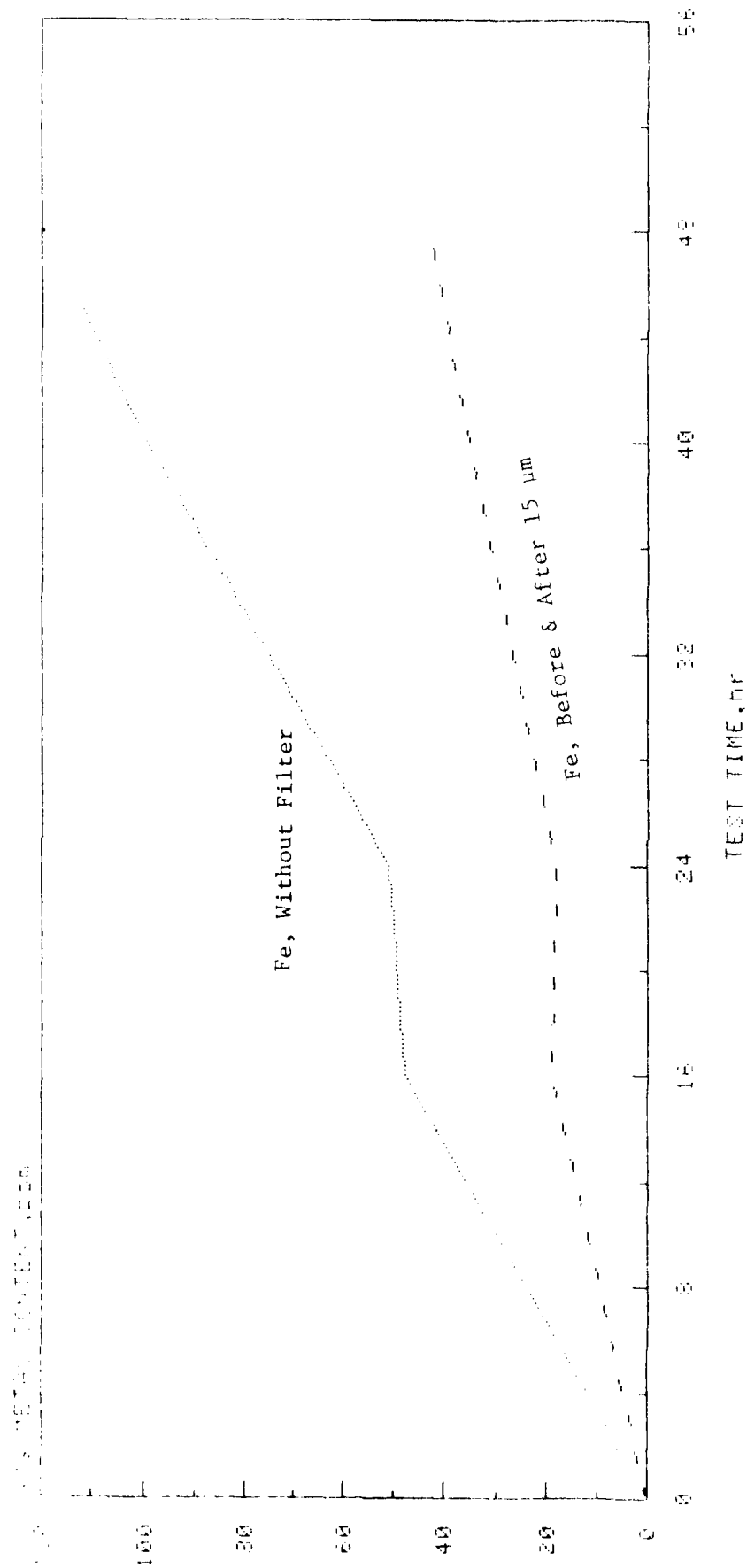
FIGURE 29. AVERAGE IRON CONTENTS DURING WEAR TESTS
WITH LUBRICANT O-82-3

Energy Dispersive X-ray Fluorescence (XRF). Hot-wall deposit scraping samples were collected at the end of certain tests and were analyzed for trace amounts of specified elements depending on the wear coupons employed during the test. For instance a test having 4616/M-50 wear was analyzed for iron (Fe), chromium (Cr), molybdenum (Mo), copper (Cu) and zinc (Zn). Likewise, a test having 9310/9310 wear was analyzed for iron (Fe), nickel (Ni), chromium (Cr) and manganese (Mn), and a test having silver/M-50 wear was analyzed for silver (Ag), iron (Fe), chromium (Cr), molybdenum (Mo) and vanadium (V). Only selected tests having sufficient amounts of deposits were employed for these analyses. This effort was an attempt to shed light on the significance of various elements or alloying elements in the wear metals on deposit formation. Shown in Table 14 are the trace amounts of the elements of interest determined in the three tests whereby analyses were feasible. For the 4616/M-50 wear test with 15 μm filtration, it is seen that the deposits were high in Cu and also contained a trace amount of Zn which were both derived from the AMS 4616 bronze wear coupon. The 0.20 wt percent Fe was also of significance and was probably derived from the M-50 steel coupon wear. The 9310/9310 wear test, also with 15 μm filtration, revealed a fair amount of Fe and also had 0.10 wt percent Ni, which is the primary alloying element in SAE 9310 steel. The chemical composition of this steel specifies 3.45 percent. The Ag/M-50 wear test without filtration showed a very high amount of Fe and molybdenum in the deposits, but no Ag was detected. It is interesting that molybdenum is the primary alloying element of M-50 steel. On the other hand, chromium, a close secondary alloying element to molybdenum, was only detected in a very minute amount. Also the silver coupon did not contribute any measurable amount of trace silver to the deposits.

Worthy of mention is the fact that the silver wear in tests employing silver coupons appeared to be quite different than noted for the other wear coupons. The silver appeared to have large pieces of the material torn from the coupons and it appeared to be a delamination-type wear rather than the normal rubbing wear noted for the other wear coupons. Many of the tests employing silver wear had appreciable amounts of large silver particles in the bottom of the lubricant sump and on the test-oil pump screen, but very little silver was detected in the lubricant samples by AA analysis.

TABLE 14.   TRACE ELEMENT AMOUNTS IN DEPOSIT
SCRAPINGS FROM HOT-WALL SURFACES

Wear Coupon Material, upper/lower	Trace Amount of Element in Deposit, wt %								
	Fe	Cr	Mo	Ni	Mn	V	Cu	Zn	Ag
4616/M-50*	0.20	<.01	<.01	–	–	–	1.49	0.04	–
9310/9310*	0.16	<.05	–	0.10	0.06	–	–	–	–
Ag/M-50**	1.09	<.05	1.10	–	–	<.05	–	–	0

 * With 15 µm filtration.
** Without filtration.

Needless to say, these data show interesting implications of various alloying elements toward lubricant deposition and certainly seem worthy of further investigation.

Exploratory Tests

About midway through the program severe breakdown of lubricant 0-77-4 during testing, as evidenced by significant viscosity and NN increases, was experienced. Also considerable scatter, especially in viscosity and NN results, for some of these tests were noted. Therefore, the temperature recorder and associated thermocouples were rechecked for proper calibration to assure that proper temperatures of the hot-wall deposit surface and test lubricant were being attained. Also, the deposit surface temperatures were rechecked by using thermocouples spot-welded to the heated surfaces. The results of these checks assured that the equipment was operating satisfactorily and that the proper temperatures were being achieved. This also indicated that the breakdown of the lubricant was indeed a characteristic and not the result of improper test temperatures. This led to the hypothesis that the "breakdown" of some of the lubricants was near 288°C (550°F), the approximate maintained temperature of the deposit surface, and consequently breakdown of the lubricant might or might not occur during testing. Therefore, two exploratory tests were performed to elucidate on these happenings and the results are shown in Table 15. As seen, the 6°C (10°F) drop in the hot-wall deposit surface, all other test conditions unchanged, did significantly mitigate all three test results. This was especially noticed for lubricant 0-77-4. It appears from these limited amount of nonwear, no-filtration tests that lowering the hot-wall temperature approximately 6°C alleviates considerable breakdown of these two lubricants. A similar severe breakdown was also noted for lubricant 0-82-3, but the amount of lubricant available was limited and was utilized in mitigation of wear-metal effects testing.

TABLE 15.   COMPARISON OF HOT-WALL DEPOSITION TEST RESULTS AT
LOWER DEPOSIT SURFACE TEMPERATURE
(No Wear, No Filtration)

Deposit Surface Temp, °C (°F)	Avg Deposit Rating	Avg 40°C Vis Incr, %	Avg NN Change, mg KOH/g	Remarks
Lubricant 0-77-4				
288 (550)	32	106.7	15.43	Two tests
282 (540	16	3.5	1.71	One test
Lubricant 0-82-2				
288 (550)	51	8.1	2.16	Three tests
282 (540)	31	6.8	1.62	One test

SECTION VI

CONCLUSIONS

A detailed description of the hot-wall deposition test rig and its operation as well as selected wear metals are discussed. The selected test method for evaluating deposition and degradation characteristics of turbine engine lubricants both with and without typical wear metals and also with or without filtration is also discussed, and appropriate test data are presented. The approach employed in selecting filtration tests for the mitigation of wear-metal effects phase of the program is also presented.

On the basis of hot-wall deposition tests employing eight MIL-L-7808 or MIL-L-7808-type turbine engine lubricants, the following conclusions can be made:

- The test rig, modified with a newly designed hot-wall section and using a recently developed wear generator, is appropriate for evaluating deposition and degradation of turbine engine lubricants. There is limited evidence that a slightly lower hot-wall temperature, to prevent severe breakdown of some of the lubricants, might reveal improvement of the test.

- The wear generator and selected wear coupons did not demonstrate good repeatability, as was experienced on a companion program using only mild steel wear coupons. It is believed that the difference in wear coupon hardnesses on this program contributed to the poor repeatability. For the relatively soft SAE 9310 steel wear coupons, fairly good repeatability was experienced. The harder M-50 steel produced much lower wear with very poor repeatability. Silver wear coupons were very soft and demonstrated severe deformation with a different wear mechanism, appearing to be what would be defined as delamination-type wear. The AMS 4616 bronze wear coupons were harder than silver, but much softer than either SAE 9310 or M-50 coupons and again demonstrated poor repeatability.

- A statistically significant deleterious effect for metal wear on lubricant deposition was demonstrated. Considering individual metal types, adjusted deposit rating means (Fig. 11) indicate negligible effects for silver and 4616 bronze and appreciable effects for the 9310 and M-50 steels. The greater influence in promoting deposits shown by 9310 may have been solely attributable to its greater susceptibility to wear versus that for M-50.

- Statistical analysis of the hot-wall deposition data showed that micronic filtration does mitigate the effects of wear metals on deposition, with no clear differences seen between the effects of 3 μm filtration versus 15 μm filtration. For lubricant viscosity increase, the 3 μm filter showed a questionable advantage over either 15 μm filtration or no filtration. No filtration differences were apparent when analyzing neutralization number changes for the lubricants.

- Trace metal content in lubricant samples by AA showed a general improvement (less metal particles) in both 15 μm and 3 μm filtration-wear tests over nonfiltration conditions. Many of the wear tests did not show a significant difference in metal content between the two levels of filtration, nor between the upstream and downstream (before and after the filter) lubricant samples. This suggests that there were many small particles of metal in the lubricant in suspension that passed readily through the filters, or that few large particles were circulated by the lubricant system. Essentially no trace silver appeared in any of the lubricant samples analyzed regardless of the amount of silver coupon wear present. Large silver particles were visible in the lubricant sump, but were not detected by AA in the lubricant flowstream.

- Trace metal content in deposit scrapings revealed high concentrations of some of the alloying elements from the wear coupon materials. This suggests that the elements contribute to deposition at varying degrees and defining the mechanism involved needs to be pursued.

SECTION VII

RECOMMENDATIONS

The deleterious effects of typical oil-wetted wear metals and helpful effects of micronic filtration on turbine engine lubricant deposition certainly raises questions worthy of further investigation. The fact that various lubricants, which undoubtedly have varying formulations, displayed different deposition and degradation characteristics would be of interest to lubricant formulators. A study to determine the effects of lubricant base-stock and various lubricant additives on deposition is recommended. Since the use of lubricant additives such as metal deactivators to mitigate the effects of wear metal on lubricant deposition was not pursued in this program, it would seem worthy of a preplanned orderly investigation. Such an investigation should be developed in cooperation with key lubricant formulators and major additive suppliers.

In this program, some alloying elements present in the wear metals studied appeared to be deleterious toward lubricant deposition. Therefore, a carefully planned investigation of the effects of appropriate single elements toward deposition and ways to mitigate these effects would seem beneficial.

The "breakpoint" of various MIL-L-7808 lubricants as determined by severe increases in viscosity and neutralization number was shown to be below the hot-surface temperature employed in this study. The implications and significance of this toward turbine engine lubricant qualification need to be clarified..

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APPENDIX

TEST SUMMARY DATA FOR EIGHT LUBRICANTS

The following tables contain pertinent data for all eight of the lubricants employed in this program. Some tests that were questionable as to validity, were performed at other than "standardized test conditions, and/or were of an exploratory nature are not included in the tables.

Detailed test data sheets, with deposit specimen color photographs, from which these tables of data were derived, were submitted to AFWAL for record with the monthly R&D Status Reports.

TABLE 16. HOT-WALL DEPOSITION TEST SUMMARY DATA
FOR LUBRICANT O-71-11

Test Parameters			Test Results			
Wear Coupon Material, upper/lower	Coupon Wear, upper/lower, g	Specimen Drain, ml/min	Deposit Rating	40°C Vis Incr, %	NN Change, mg KOH/g	Test No.
None None	None None	16 17	13.0 14.0	-3.8 -4.6	3.13 2.94	123-1-30 124-2-29
M-50/M-50 M-50/M-50	0.013/0.019 0.003/0.005	33 16	15.0 13.0	-5.7 -5.7	3.74 3.74	213-1-34 214-2-35
9310/9310 9310/9310	0.441/0.213 0.172/0.001	23 20	59.0 61.5	-1.8 -4.5	4.85 2.75	151-1-33 152-2-32
Silver/M-50 Silver/M-50	1.761/0.005 1.812/0.011	19 12	15.0 16.0	-3.5 -5.3	3.98 3.14	153-1-33 154-2-32
4616/M-50 4616/M-50	0.004/0.011 0.013/0.003	18 16	17.5 21.0	-3.7 -4.3	3.47 3.45	155-1-33 156-2-32

TABLE 17. HOT-WALL DEPOSITION TEST SUMMARY DATA
FOR LUBRICANT O-76-9

	Test Parameters			Test Results			
Wear Coupon Material, upper/lower	Coupon Wear upper/lower, g	Specimen Drain, ml/min		Deposit Rating	40°C Vis Incr, %	NN Change, mg KOH/g	Test No.
None	None	16		15.5	1.3	3.23	197-1-34
None	None	16		16.0	-0.4	2.83	198-2-36
M-50/M-50	0.048/0.108	22		96.5	54.7	30.82	199-1-34
M-50/M-50	0.014/0.028	12		65.0	9.0	9.78	200-2-35
M-50/M-50	0.025/0.045	13		90.0	48.1	30.36	208-2-35
9310/9310	0.002/0.457	17		115.5	36.7	28.36	201-1-34
9310/9310	0.075/0.322	14		107.5	48.6	32.15	202-2-35
Silver/M-50	0.032/0.072	13		100.5	28.9	22.17	204-2-35
Silver/M-50	0.048/0.055	20		96.5	40.0	28.46	205-1-34
4616/M-50	0.050/0.093	11		91.0	21.2	17.69	206-2-35
4616/M-50	0.038/0.142	16		97.5	23.8	30.68	207-1-34

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TABLE 18. HOT-WALL DEPOSITION TEST SUMMARY DATA
FOR LUBRICANT O-77-4

Test Parameters			Test Results			
Wear Coupon Material, upper/lower	Coupon Wear, upper/lower, g	Specimen Drain, ml/min	Deposit Rating	40°C Vis Incr, %	NN Change, mg KOH/g	Test No.
Without Filtration						
None	None	26	27.0	171.0	19.17	183-1-33
None	None	24	36.0	42.4	11.68	184-2-32
None	None	23	16.0	3.5	1.71	230-2-35*
M-50/M-50	0.007/0.025	27	65.5	118.4	13.43	185-1-34
M-50/M-50	0.013/0.037	22	58.0	5.7	1.51	186-2-35
M-50/M-50	0.017/0.026	19	64.0	3.9	1.54	195-1-34
9310/9310	0/0.329	22	91.0	66.3	13.76	187-1-34
9310/9310	0.001/0.489	23	66.5	4.4	1.44	188-2-35
9310/9310	0.218/0.007	18	72.5	4.4	2.04	196-2-36
Silver/M-50	0.017/0.016	23	104.0	63.4	13.87	189-1-34
Silver/M-50	0.025/0.023	22	96.5	120.7	16.43	190-2-35
4616/M-50	0.082/0.015	20	97.0	85.6	13.21	191-1-34
4616/M-50	0.580/0.023	22	113.0	138.4	15.30	192-2-36
With 15 μm Filtration						
4616/M-50	0.137/0.012	15	60.0	77.1	13.56	225-1-36
4616/M-50	0.467/0.036	22	98.5	156.5	33.76	228-2-35
4616/M-50	0.441/0.027	22	94.5	70.6	14.68	232-2-35
With 3 μm Filtration						
4616/M-50	0.238/0.032	20	84.5	60.2	12.85	227-1-37

* Heating fluid controlled at temperature 10°F below normal.

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TABLE 19. HOT-WALL DEPOSITION TEST SUMMARY DATA
FOR LUBRICANT 0-79-16

	Test Parameters			Test Results			
Wear Coupon Material, upper/lower	Coupon Wear, upper/lower, g	Specimen Drain, ml/min	Deposit Rating	40°C Vis Incr, %	NN Change, mg KOH/g	Test No.	
Without Filtration							
None	None	24	35.0	7.2	0.30	111-1-29	
None	None	20	29.0	8.1	0.20	112-2-30	
M-50/M-50	0.065/0.013	25	84.0	9.4	0.76	211-1-34	
M-50/M-50	0.001/0.001	22	63.0	8.5	0.50	212-2-35	
9310/9310	0.360/0.817	28	110.5	11.8	1.17	145-1-31	
9310/9310	0.340/0.890	22	113.5	12.1	1.15	146-2-32	
/M-50	0.025/0.022	29	66.5	9.0	0.55	147-1-31	
/M-50	0.642/0.009	19	68.5	8.8	0.48	148-2-32	
/M-50	0.128/0.030	33	82.5	10.1	0.92	149-1-31	
/M-50	0.005/0.022	19	79.5	9.3	0.57	150-2-32	
With 15 μm Filtration							
9310/9310	0.370/0.593	22	90.0	6.5	0.58	237-1-36	
9310/9310	0.275/0.580	13	90.0	6.1	0.57	238-2-35	
With 3 μm Filtration							
9310/9310	0.385/0.634	19	90.5	9.0	0.44	239-1-38	
9310/9310	0.303/0.568	23	87.5	9.0	0.50	240-2-35	

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TABLE 20. HOT-WALL DEPOSITION TEST SUMMARY RESULTS
FOR LUBRICANT O-79-17

| | Test Parameters | | Test Results | | | |
Wear Coupon Material, upper/lower	Coupon Wear, upper/lower, %	Specimen Drain, ml/min	Deposit Rating	40°C Vis Incr, %	SN Change, mg KOH/g	Test No.
		Without Filtration				
None	None	33	36.0	16.1	0.47	101-1-27
None	None	29	41.0	9.4*	0.51*	102-2-28
M-50/M-50	0.096/0.020	25	93.0	17.8	0.65	215-1-36
M-50/M-50	0.091/0.030	17	90.0	17.3	0.63	216-2-35
9310/9310	0.409/0.269	21	110.5	20.5	0.83	139-1-31
9310/9310	0.318/0.638	26	108.0	20.3	1.18	140-2-32
Silver/M-50	0.123/0.086	29	108.0	12.4	0.66	141-1-31
Silver/M-50	0.068/0.305	21	112.0	16.6	0.89	142-2-32
4616/M-50	0.017/0.402	15	99.0	18.4	0.83	143-1-31
4616/M-50	0.043/0.043	22	100.0	17.8	1.20	144-2-32
		With 15 µm Filtration				
M-50/M-50	0.041/0.031	37	88.0	14.8	0.66	231-1-37
M-50/M-50	0.017/0.006	24	57.0	12.7	0.57	234-2-35
.../M-50	0.877/0.028	33	47.0	13.9	0.64	229-1-37
.../M-50	0.007/0.028	23	47.0	15.1	0.68	233-1-36

*No results because of accidental dilution of lubricant in sump during flow check.
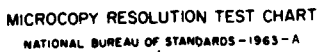
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TABLE 21. HOT-WALL DEPOSITION TEST SUMMARY DATA
FOR LUBRICANT O-79-20

	Test Parameters		Test Results			
Wear Coupon Material, upper/lower	Coupon Wear, upper/lower, g	Specimen Drain, ml/min	Deposit Rating	40°C Vis Incr, %	NN Change, mg KOH/g	Test No.
Without Filtration						
None	None	28	49.0	8.5	0.41	109-1-29
None	None	30	46.5	8.7	0.43	110-2-30
M-50/M-50	0.051/0.036	22	87.0	6.2	0.55	217-1-36
M-50/M-50	0.032/0.018	24	82.5	5.3	0.44	218-2-35
9310/9310	0.424/0.310	37	117.5	8.9	1.32	133-1-30
9310/9310	0.090/0.606	25	121.0	9.1	1.32	134-2-29
Silver/M-50	0.020/0.012	25	64.5	6.2	0.52	220-2-35
Silver/M-50	0.008/0.093	25	92.5	5.1	0.71	241-1-38
4616/M-50	0.008/0.054	26	71.5	8.2	0.66	157-1-33
4616/M-50	0.247/0.029	30	71.0	8.1	0.82	158-2-32
With 15 μm Filtration						
9310/9310	0.384/0.520	22	96.0	8.6	0.62	221-1-36
9310/9310	0.194/0.438	24	96.0	7.6	0.66	222-2-35
With 3 μm Filtration						
9310/9310	0.435/0.283	26	88.0	8.2	0.65	223-1-36
9310/9310	0.270/0.587	24	90.0	10.0	1.17	224-2-35

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TABLE 22. HOT-WALL DEPOSITION TEST SUMMARY DATA
FOR LUBRICANT O-82-2

Wear Coupon Material, upper/lower	Coupon Wear, upper/lower, g	Specimen Drain, ml/min	Deposit Rating	40°C Vis Incr, %	NN Change, mg KOH/g	Test No.
	Test Parameters			Test Results		
		Without Filtration				
None	None	25	57.5	8.0	2.21	159-1-33
None	None	22	52.0	7.9	2.10	164-2-32
None	None	24	43.0	8.3	2.16	219-1-36
None	None	18	31.0	6.8	1.62	242-2-35*
M-50/M-50	0.019/0.045	33	60.0	8.4	2.44	162-2-32
M-50/M-50	0.010/0.179	32	60.0	8.2	2.14	163-1-33
9310/9310	0.038/1.108	30	81.0	10.2	3.08	165-1-33
9310/9310	0.035/1.120	29	84.0	8.3	2.65	166-2-32
Silver/M-50	0.263/0.048	26	60.0	7.7	1.59	167-1-33
Silver/M-50	0.074/0.033	27	60.0	8.3	1.90	171-1-33
4616/M-50	0.005/0.039	30	60.0	8.8	1.69	169-1-33
4616/M-50	0.006/0.007	19	60.0	8.2	1.54	170-2-32
		With 3 μm Filtration				
None	None	25	44.0	7.8	2.38	243-2-35

* Heating fluid controlled at temperature 10°F below normal.

TABLE 23. HOT-WALL DEPOSITION TEST SUMMARY DATA
FOR LUBRICANT O-82-3

	Test Parameters			Test Results			
Wear Coupon Material, upper/lower	Coupon Wear, upper/lower, g	Specimen Drain, ml/min		Deposit Rating	40°C Vis Incr, %	NN Change, mg KOH/g	Test No.
Without Filtration							
None	None	22		11.0	15.8	0.85	172-2-32
None	None	26		10.0	15.0	0.78	177-1-33
M-50/M-50	0.052/0.081	25		55.0	163.4	10.89	173-1-33
M-50/M-50	0.050/0.055	24		57.5	114.0	9.79	174-2-32
9310/9310	0.482/0.554	25		100.0	145.5	8.72	175-1-33
9310/9310	0.340/0.324	27		96.5	171.4	8.58	176-2-32
Silver/M-50	0.005/0.016	22		36.0	20.8	1.66	178-2-32
Silver/M-50	0.012/0.056	26		27.0	182.3	11.25	181-1-33
4616/M-50	0.096/0.095	26		70.5	41.2	3.87	179-1-33
4616/M-50	0.107/0.037	21		60.0	16.2	0.76	180-2-32*
4616/M-50	0.191/0.039	22		60.0	17.7	0.77	182-2-32*
With 15 μm Filtration							
9310/9310	0.508/0.609	17		83.5	83.7	7.60	235-1-36
9310/9310	0.250/0.407	19		56.0	71.9	7.50	236-2-35

* Sump pump intake screen was completely covered with deposits and bronze wear particles at end of test. Suspected oil flow restriction by deposits.

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