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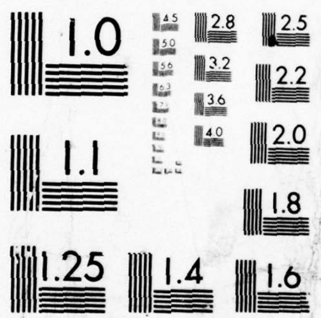

MICROCOPY RESOLUTION TEST CHART

NATIONAL BUREAU OF STANDARDS-1963-A

CONTRACT NO. DAAK70-77-C-0034

OCTOBER 1978

PERFORMANCE OF AUTOMOTIVE WHEEL BEARING GREASES

FINAL REPORT

SKF INDUSTRIES, INC. REPORT NO. AL78T022

BY

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FOR

U. S. ARMY MOBILITY EQUIPMENT
RESEARCH AND DEVELOPMENT COMMAND
FORT BELVOIR, VIRGINIA

(12)

RESEARCH REPORT

ON

PERFORMANCE OF AUTOMOTIVE WHEEL BEARING GREASES.

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SUMMARY

The objective of this program is to establish the relative performance characteristics of six greases in a simulated automotive front wheel tapered roller bearing environment under highly accelerated laboratory type test conditions. The test conditions have been designed to precipitate lubricant relatable failures. The lubrication characteristics of these greases are primarily rated on the basis of endurance of the bearing/grease systems. In addition, the residual grease and the rolling contact surfaces of selected bearings have been examined to further support the endurance test results. By this means, a data base has been provided for the comparative evaluation of newly developed candidate greases. Briefly, this program has been conducted in three parts as follows:

Part I deals with the evaluation of the test greases in a test machine designed to simulate the general configuration of an automotive front wheel bearing hub. The test bearings are a pair of tapered roller bearings of the size normally found in an automotive application, which are run at an inner ring speed of 800 rpm. This is equivalent to 105kph. The hub is loaded under a continuous radial force equivalent to 150% of the vehicle curb weight. An additional cyclic axial cornering force equal to 30% of the radial force is applied for 1-1/2 minutes every 5 minutes. The ambient environment is artifically elevated to 394 $^{\circ}$K (250°F) to further accelerate the test cycle.

Post test visual observations were completed on each pair of bearings to establish (a) the amount and condition of the residual grease remaining on each bearing, and (b) the extent of the damage to the rolling contact surfaces.

The lives of each test group have been statistically estimated using a maximum likelihood technique assuming the existance of a Weibull distribution of the data. The L_{10} life of each group of bearings based upon this analysis is considered as being a function of grease performance. These data were analyzed further using a statistical significance test to establish the validity of the differences noted between the L_{10} lifes of the bearing groups.

Part II included a more detailed study of representative bearings to define the degree of deterioration experienced on the rolling contact surfaces of the bearings lubricated with each grease. Photomicrographs made with a Scanning Electron Microscope show the changes to the surface morphology of the cone rolling contact

Surfaces. Observations as to the relative lubrication efficiency of the sample greases based on the degree of protection provided to the bearing surfaces have been established and are used to supplement the life data presented in Part I.

Part III presents information on the changes occurring to the grease chemistry and structure from use in an elevated temperature bearing environment. Samples of residual grease removed from the representative bearings discussed in Part II have been analyzed to determine changes in penetration, neutralization number and oil content as a measure of grease deterioration.

PREFACE

This report presents the results of a study conducted by SKF Technology Services for the A26142, U. S. Army Mobility Equipment Research and Development Command, Fort Belvoir, Virginia 22060 under Contract No. DAAK70-77-C-0034. This report encompasses effort conducted from March 1977 to October 1978.

Technical direction for the U. S. Army was provided by Mr. John Doner (W26R9D) the Contracting Officers Representative Lab 2000 (DRXFB-GL).

The principal investigators from the SKF Mechanical Laboratories who worked on this project were Mr. N. J. Ninos - Scientist and Project Leader; Mr. F. R. Morrison - Supervisor, under whose direction the work was accomplished; Mr. H. Dalal - Sr. Scientist; Mr. D. Hahn - Technician who conducted the Scanning Electron Microscope studies; Dr. J. Rumierz - Section Supervisor Chemistry who directed the microanalysis of the used grease samples; and Mr. J. McCool - Senior Mathematician who performed the statistical data analysis.

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I. INTRODUCTION

A. STATEMENT OF PROBLEM

The grease utilized by the U. S. Army for automotive wheel bearing applications is procured under Military Specification MIL-G-10924C. Currently, the cost effectiveness of the Army's established wheel bearing relubrication intervals is being examined and questions have been raised concerning the feasibility of utilizing the greased-for-life wheel bearing concept. Unfortunately, the data base concerning wheel bearing performance with military greases is insufficient to allow the formulation of responses to these questions with a satisfactory level of confidence.

Commercial automotive companies have also been concerned with various aspects of these issues so that there exists a sizeable amount of data in the non-military area which are pertinent to the questions at hand. The utilization of these data requires the establishment of the relative performance potential of the military grease with its commercial counterparts.

This program was conducted to provide a data base of the relative lubrication capabilities of a number of greases which could be utilized in automotive front wheel bearing applications. Six greases were evaluated, ie. one commercial product, and five greases conforming to certain military specifications. The greases were selected by Mobility Equipment Research and Development Command (MERADCOM). Test quantities of the five military greases were provided by the government, while the commercial product was purchased from a lubricant supplier. These six greases are identified as follows:

GREASE CODE	IDENTIFICATION
A	MIL-G-10924C
B	MIL-G-10924C
C	COMMERCIAL PRODUCT
D	MIL-G-81322B, AM3
E	MIL-G-23549A/ASG
F	MIL-G-10924D (proposed)

B. METHOD OF APPROACH

To facilitate the evaluation of the lubrication characteristics of the greases, accelerated life tests were conducted employing paired tapered roller bearings as test specimens. These were mounted in a wheel hub configuration simulating a typical automotive front wheel application. The test specimens were standard production bearings of the LM12749/LM12710 and L68149/L68110 designation produced by the Tyson Tapered Bearings Division of SKF Industries, Inc.

To obtain a sufficient amount of data within a practical period of time, testing was accelerated by applying loads of a higher magnitude than would normally be applied in automotive service; and by artificially elevating the ambient temperature surrounding the hub assembly. The bearings were run either to failure or to a time up life of 300 hours, which represent 14.4 million revolutions or 32,000 kilometers of operation. The theoretical L_{10} life of the system ie. both bearings is 11.2 million revolutions as shown by the calculations in Appendix 1.

Twenty pairs of bearings were run with each grease sample to obtain a statistically reliable data base from which the L_{10} life of the population was determined with a high level of confidence. At the conclusion of this series of investigations, the L_{10} lives of the six grease groups were analyzed further to assess the significance of the life differences found.

All bearings were examined visually at the conclusion of the test at magnifications up to 30X. The condition of the residual grease from the bearings and the extent of damage to the rolling contact surfaces has been described.

A more detailed examination was conducted on four bearings from each group after a finite length of operation. The purpose of this examination was to assess the extent of grease deterioration through microanalysis; and the degree of physical damage to the rolling contact surfaces observable at high power (250 and 1000X magnification). Scanning electron photomicrographs of the cone running surfaces have been comparitively examined and the degree of microwear and other surface damage characteristics for each type grease has been established. These additional data support the life results which are the basis of evaluation of these greases, and provide a data base which can be used in the evaluation of proposed candidate greases.

II. INVESTIGATION

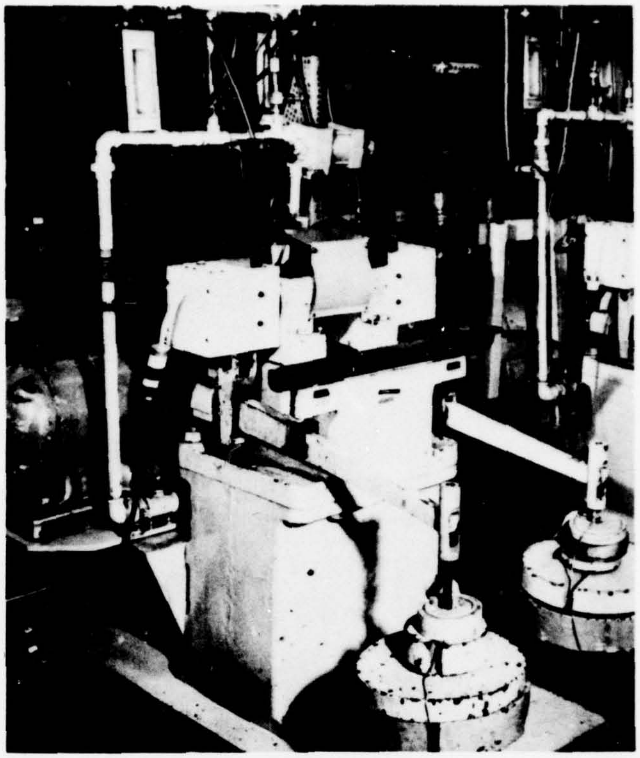
A. PART 1 - ENDURANCE EVALUATION

The tests were conducted on a basic SKF Industries, Inc. R-2 Endurance Test Machine which was modified to accept a simulated front wheel hub assembly. A detailed description of the design and operation of this test machine, the test procedures and the conditions under which the tests were performed in order to evaluate the lubrication characteristics of each grease are presented in the following sections.

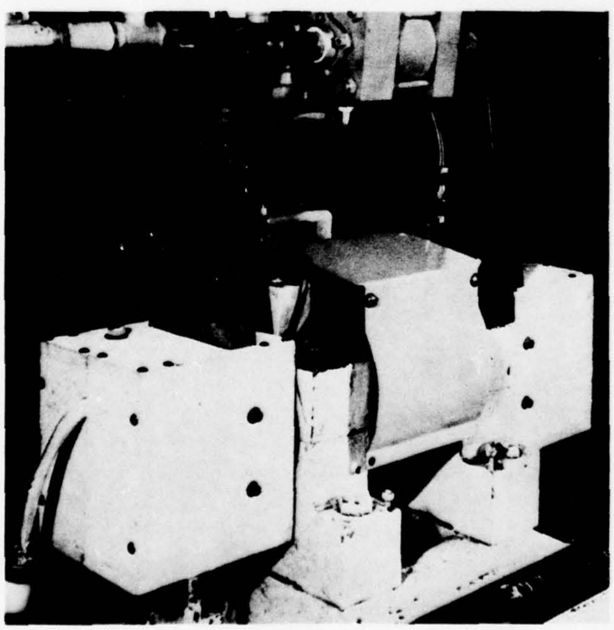
1. ENDURANCE TEST MACHINE

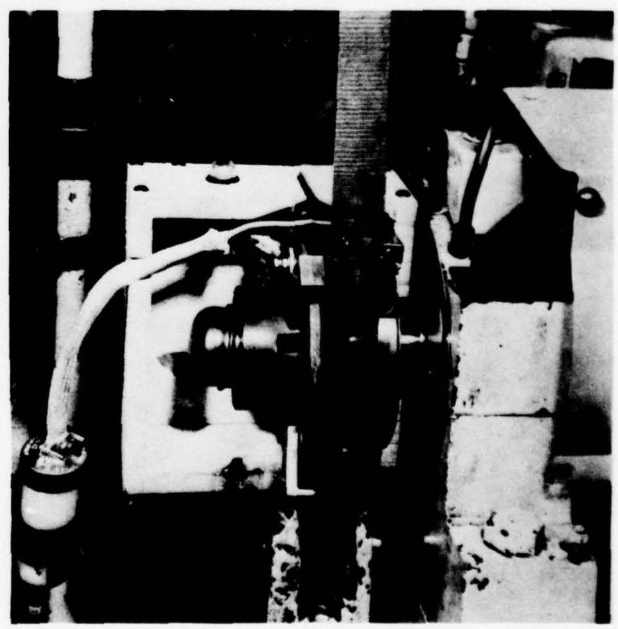
The basic configuration of the test machine consists of a centrally belt driven horizontal arbor which is supported by two cylindrical roller bearings. Photographic views of the machine are shown in Figure 1. A hub containing a pair of tapered roller bearing test specimens is mounted on each end of the arbor as shown in the assembly drawing of Figure 2. A constant radial force is applied to each hub assembly by a dead weight through a lever and linkage arrangement. A thrust force is applied inward by an air cylinder mounted between the hubs at a prescribed distance from the bearing axis. This offset simulates a cornering force on the hub assembly as would be produced at the tire periphery when a car turns. The thrust force is applied cyclically every five minutes for 1-1/2 minutes duration.

A Chromalox 500 Watt ring heater, fastened to the side of the load arm, surrounds the hub as shown in Figure 2. It provides additional heat, over and above that caused by internal bearing friction, to bring the bearing temperature to the required level of operation. Power to the dual element heater is controlled manually through a Powerstat. One element of the heater is constantly on and supplies that amount of heat needed to bring the operating temperature of the test bearings to within 10 to 15°C of the specified level. The second element, powered through the same Powerstat, is thermostatically controlled to maintain the total temperature at the prescribed operating level. An insulated housing, Figure 1b, surrounding each hub assembly maintains the temperature at an even level and prevents rapid thermal fluctuations.



(a) Overall View





(b) Enclosed Test Head (c) Test Hub and Heater

Figure 1. Photographs of Front Wheel Bearing Test Machine

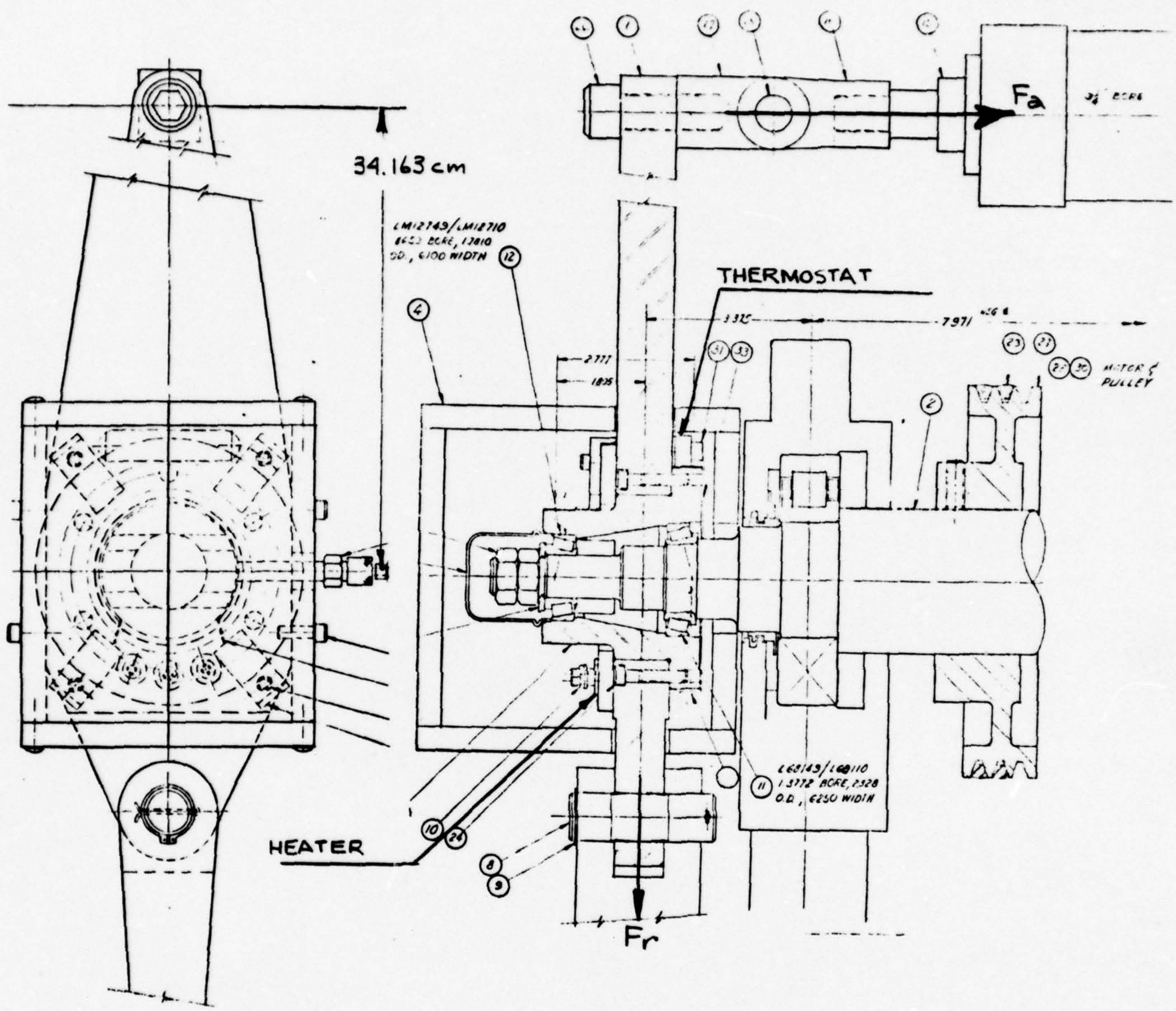


Figure 2. Schematic of Hub Assembly Front Wheel Bearing Grease Test Machine

The operating temperature of each bearing is measured by an iron-constantan thermocouple in contact with the outer ring (cup) outer diameter surface. The temperature is monitored and recorded by an automated test floor control system which contains a Data General Nova 800 mini-computer as a central processing unit. The control system is programmed to provide alarms and/or to stop a machine whenever the bearing operating temperature exceeds preset temperature limits. In addition, a special subroutine, known as the Temperature Rate of Increase Monitor (TRIM), was used to detect an impending failure as the result of a lubrication deficiency. The TRIM, which was developed as a means of anticipating the ultimate failure of the grease pack contained in a bearing, automatically terminates a test when the rate of temperature rise is greater than or equal to a preset limit for a time period sufficient to produce a preset absolute temperature increase. In this study, the TRIM values were $1^{o}K$ per minute rise with a maximum increase of $12^{o}K$ Concurrently, the maximum temperature of operation was set at $423^{o}K$.

2. ENDURANCE TEST PROCEDURE

The test conditions and the procedure employed are based upon an industrial method used to evaluate the endurance of commercial wheel bearings. In this test procedure, a hub assembly is subjected to a radial load equivalent to 150% of the vehicle curb weight. In addition, a thrust load, or cornering load equal to 30% of the radial load is applied intermittently at a distance from the center of the bearing axis which is equivalent to the tire radius.

On the basis of the weight of a medium size sedan, the bearings were subjected to a constant radial load of 8.34 kN (1875 lbs.f). In addition, a thrust load of 2.49 kN (560 lbs.f.) was applied at a distance of 34.2 cm (13.45 inches) from the horizontal centerline of the bearing axis every 5 minutes for a duration of 1-1/2 minutes or 30% of the time.

The bearings were run at an inner ring speed of 800 rpm which is approximately equivalent to a vehicle speed of 105 k.p.h. (65 mph). The bearing operating temperature was maintained at $394^{o}K \pm 2^{o}K$.

Each pair of test bearings was lubricated with the test grease in the following manner. The bearings were packed full and 40 grams of grease was distributed in the hub cavity between the bearings. They were run to a preset time up life of 300 hours which is approximately equivalent to 32,000 kilometers (20,000 miles) or until failure, whichever occurred first. The onset of failure was defined as (a) a distinct increase in the normal operating vibration level as detected by a vibraswitch mounted on the test system (b) an increase in the noise level (c) a gradual heat imbalance reducing the power input required to heat the environment to 50% of its original value, (d) a sudden heat imbalance resulting in an increase in bearing temperature at an excessive rate as determined by the limits established in the Temperature Rate of Increase Monitor included in the test floor control computer system or (e) an increase in temperature above a preset limit of $423^{o}K$. An indication of failure with any of these modes automatically terminated the test run.

Three test rigs were employed in order to complete this study in a reasonable time interval.

3. TEST BEARING DESCRIPTION

Each grease was tested using 20 pairs of bearings of the following configuration:

Bearing No.	Basic Size mm		
	Inner Diameter	Outer Diameter	Width
LM12749/LM12710	21.979	45.974	15.494
L68149/L68110	34.981	59.974	15.875

These bearings were part of a statistically similar sample group produced according to SKF Industries, Inc. manufacturing standards and tolerances for material and geometry.

4. TEST GREASE IDENTIFICATON

Except for one product, all of the greases evaluated in this program were supplied by the government, and are identified as follows:

IDENTIFICATION OF GREASES EVALUATED

GREASE CODE	MILITARY IDENTIFICATION	
	BRANCH OR TYPE	SPECIFICATION NO.
A	U.S. Army Artillery and Wheel Brg.	MIL-G-10924C
B	U.S. Army Artillery and Wheel Brg.	MIL-G-10924C
C	Commercial Product	-
D	General Aircraft Purpose	MIL-G-81322B, AM3
E	General Purpose	MIL-G-23549A/ASG
F	Experimental	MIL-G-10924D (proposed)

The typical characteristics for these six greases are presented below:

TEST	ASTM METHOD	GREASE A	B	C	D	E	F
Penetration, 60 double strokes	D217	283	281	285	315	312	298
Dropping Point, °C	D2265	144	143	260+	260+	260+	144
Oil Separation, %	D1742	6.0	5.2	3.0	3.1	2.9	2.4
Evaporation, %	D972	5.8	5.3	2.8	0.2	2.8	1.2
4 Ball Extreme Pressure, Load Wear Index	D2596	35.6	32.1	40.0	40.5	92.0	37.9
4 Ball Wear, Scar Diameter, mm	D2266	0.53	0.55	0.40	0.45	0.49	0.47
Base Oil Viscosity, 40°C cS		13.3	13.3	129.3	29.3	330.7	38.4
Base Oil Viscosity, 100°C cS		2.94	2.94	13.6	5.47	29.1	5.17
Base Oil Type N = Naphthenic, P = Paraffinic, SH= Synthetic Hydrocarbon		N	N	P	SH	P	N
Thickener Type Ca = Calcium, Li = Lithium, Clay = Bentonite Clay		Ca	Ca	Li	Clay	Li	Ca

5. OBSERVATION DETAILS

The ability of a grease to lubricate properly has been established through the observation of changes to the original rolling contact surface morphology. The relative effectiveness of each grease is based upon the length of operation of each group of bearings; and the magnitude and severity of deterioration observed. Each grease has been rated according to the following methods of observation.

At the conclusion of a test, a bearing specimen was examined visually to assess the quantity and condition of the grease remaining in the bearing. In addition, the bearing was examined to establish the mode of failure without cleaning it or disassembling the hardware. After the 20 bearing sample was run off, two bearings of each size representing a finite length of operation were chosen for further analysis to be explained in Parts II and III. The remainder of the group were degreased and the bearings disassembled. The hardware was reexamined optically up to 30X magnification to note what specific damage had occurred to the rolling contact surfaces. Variations in appearance were defined and documented.

Post test observation details are presented in Tables I to VI. The tables, in general describe the quantity and condition of the grease remaining on the running surfaces, the damage to the rolling contacts, the number of hours each bearing ran and the reason for terminating the test.

TABLE I

SUMMARY OF FRONT WHEEL BEARING GREASE TESTS

Post Test Observations

Group 1: Grease "A"

Series No.	Outboard Bearing - LM12700 Lubricant Condition	Outboard Bearing - LM12700 Bearing Condition	Inboard Bearing - L68100 Lubricant Condition	Inboard Bearing - L68100 Bearing Condition	Hours Run	Reason For Shutdown
101	Dry	Gross Overtemperature Failure	Light Oil Film	Good	194	High Temp.
102	Dry	Gross Overtemperature Failure	Light Oil Film	Cone Spalled	133	Vibration
103	Light Oil Film	Fair Grease Deteriorated	Light Oil Film	Cup and Cone Spalled	101	Vibration
104	Light Oil Film	Good	Light Oil Film	Cone Spalled	129	Vibration
105	Light Oil Film	Good	Light Oil Film	Cup Spalled	214	Vibration
106	Residual Grease Film	Good	Residual Grease Film	Cone and Roller Spalled	77	Vibration
107	Oil Film, Some Residual Grease	Good	Residual Grease Film	Cone Spalled	115	High Temp.
108	Dry	Gross Overtemperature Failure	Partial Oil Film/Dry	Surface Damage, lack of lubricant	53	High Temp.
109	Residual Grease Film	Good	Residual Grease Film	Microspalled	61	Noise
110	Dry	Lubrication Failure, Heat Discoloration	Light Oil Film	Good	25	High Temp.
111	Dry	Lubrication Failure, Heat Discoloration	Light Oil Film	Good	36	High Temp.
112	Dry	Lubrication Failure, Heat Discoloration	Partial Film/Dry	Microspalled	27	TRIM

TABLE I
(CONTINUED)

GROUP 1: GREASE A

SUMMARY OF FRONT WHEEL BEARING GREASE TESTS
POST TEST OBSERVATIONS

SERIES NO.	OUTBOARD BRG. - LM12700 LUBRICANT CONDITION	OUTBOARD BRG. - LM12700 BEARING CONDITION	INBOARD BRG. - L68100 LUBRICANT CONDITION	INBOARD BRG. - L68100 BEARING CONDITION	HOURS RUN	REASON FOR SHUTDOWN
113	Residual Grease Film	Cone- Small Spall	Thick Grease Film	Cone- Several Large Spalls	110	Noise
114	Dry	Microspalled	Residual Grease Film	Good	86	High Temp.
115	Dry	Lubrication Failure Heat Discoloration	Dry	Microspalled Lubrication Failure	77	TRIM
116	Residual Grease Film	Good	Residual Grease Film	Cup-Spalled	152	Vibration
117	Residual Oil Film	Good - Trace Heat Discoloration	Residual Grease Film	Cup & Cone Spalled	85	Vibration
118	Residual Grease Film Slightly Oxidized	Good - Trace Heat Discoloration	Residual Grease Film	Cup-Spalled	96	TRIM
119	Residual Grease Film	Good	Residual Grease Film	Cup-Spalled	76	Noise
120	Residual Grease Film	Good	Residual Grease Film	Cup & Cone Spalled	88	Noise

TABLE II

GROUP 2 : GREASE B

SUMMARY OF FRONT WHEEL BEARING GREASE TESTS
POST TEST OBSERVATIONS

	OUTBOARD BRG. - LM12700		INBOARD BRG. - L68100			
SERIES NO.	LUBRICANT CONDITION	BEARING CONDITION	LUBRICANT CONDITION	BEARING CONDITION	HOURS RUN	REASON FOR SHUTDOWN
201	Trace Oil Film	Lubrication Failure	Residual Grease Film	Lubrication Failure Microspalled	55	TRIM
202	Dry	Lubrication Failure	Dry	Lubrication Failure Microspalled	301	TRIM-TU
203	Dry	Lubrication Failure	Residual Grease Film	Good	106	High Temp.
204	Residual Grease Film	Good	Residual Grease Film	Cone-Large Spall Grease Oxidized	131	Noise
205	Dry	Lubrication Failure	Residual Grease Film	Good Heat Discoloration	133	TRIM
206	Residual Grease Film	Good-Grease Moderately Oxidized	Residual Grease Film	Cone-Large Spalls Grease Oxidized	119	Vibration
207	Dry	Lubrication Failure	Residual Grease Film	Good Heat Discoloration	14	High Temp.
208	Dry	Lubrication Failure	Residual Grease Film	Good	11	TRIM

TABLE II
(CONTINUED)

GROUP 2 : GREASE B

SUMMARY OF FRONT WHEEL BEARING GREASE TESTS

POST TEST OBSERVATIONS

	OUTBOARD BRG. - LM12700		INBOARD BRG. - L68100			
SERIES NO.	LUBRICANT CONDITION	BEARING CONDITION	LUBRICANT CONDITION	BEARING CONDITION	HOURS RUN	REASON FOR SHUTDOWN
209	Dry	Lubrication Failure	Light Oil Film	Good	15	TRIM
210	Dry	Lubrication Failure	Light Oil Film	Good	121	TRIM

TABLE II
(CONTINUED)

GROUP 2 : GREASE B

SUMMARY OF FRONT WHEEL BEARING GREASE TESTS
POST TEST OBSERVATIONS

SERIES NO.	OUTBOARD BRG. - LM12700 LUBRICANT CONDITION	OUTBOARD BRG. - LM12700 BEARING CONDITION	INBOARD BRG. - L68100 LUBRICANT CONDITION	INBOARD BRG. - L68100 BEARING CONDITION	HOURS RUN	REASON FOR SHUTDOWN
211	Dry	Lubrication Failure and Microspalled	Light Oil Film Mod. Oxidized	Cone - minute spall Cup-microspalled	236	TRIM
212	Residual Grease Film - Mod. Oxidized	Heat Discolored & Microspalled	Residual Grease Film, Lightly Oxidized	Cup - Spalled	138	Vibration
213	Residual Grease Film - Mod. Oxidized	Heat Discolored & Microspalled	Residual Grease Film	Cup & Cone Spalled	191	Vibration
214	Trace Oil Film	Light - Heat Discolored	Residual Grease Film	Cup & Cone Spalled	244	Vibration
215	Residual Grease Film	Heat Discolored & Microspalled	Residual Grease Film	Trace Microspalled	49	Noise
216	Residual Grease Film - Mod. Oxidized	Heat Discolored & Microspalled	Residual Grease Film	Cup - Spalled	166	Vibration
217	Residual Grease Film - Mod. Oxidized	Lubrication Failure & Microspalled	Residual Grease Film	Microspalled	131	Noise
218	Residual Grease Film	Lubrication Failure	Residual Grease Film	Microspalled	93	Noise
219	Dry, Mod. Oxidized Grease	Heat Discolored	Residual Grease Film	Cup & Cone Spalled	78	Vibration
220	Residual Grease Film, Mod. Oxidized	Heat Discolored Microspalled	Residual	Cup & Cone Spalled	109	Vibration

TABLE III

GROUP 3 : GREASE C

SUMMARY OF FRONT WHEEL BEARING GREASE TESTS

POST TEST OBSERVATIONS

SERIES NO.	OUTBOARD BRG. - LM12700		INBOARD BRG. - L68100		HOURS RUN	REASON FOR SHUTDOWN
	LUBRICANT CONDITION	BEARING CONDITION	LUBRICANT CONDITION	BEARING CONDITION		
301	Residual Grease Film	Good Heat Discolored	Residual Grease Film	Cone and Roller Spall	102	Noise
302	Residual Grease Film Moderately Oxidized	Good Grease	Residual Grease Film	Good	301	Time Up
303	Residual Grease Film	Good	Residual Grease Film	Roller Spall	51	Vibration
304	Residual Grease Film	Good	Residual Grease Film	Cone and Roller Spall	161	Noise
305	Residual Grease Film	Cone-Spall	Residual Grease Film	Good	167	TRIM
306	Residual Grease Film	Good	Residual Grease Film	Cone and Cup Spall	178	TRIM
307	Residual Grease Film	Fair Rollers Heat Discolored	Residual Grease Film	Good	132	TRIM
308	Residual Grease Film	Good	Residual Grease Film	Cone-Spall	237	Noise
309	Residual Grease Film	Good	Residual Grease Film	Good	96	TRIM
310	Residual Grease Film Slightly Oxidized	Good	Residual Grease Film	Cone-Spall	301	Time Up

TABLE III
(CONTINUED)

GROUP 3 : GREASE C

SUMMARY OF FRONT WHEEL BEARING GREASE TESTS

POST TEST OBSERVATIONS

	OUTBOARD BRG. - LM12700		INBOARD BRG. - L68100			
SERIES NO.	LUBRICANT CONDITION	BEARING CONDITION	LUBRICANT CONDITION	BEARING CONDITION	HOURS RUN	REASON FOR SHUTDOWN
311	Residual Grease Film Slightly Oxidized	Good	Residual Grease Film	Cone-Deposits of Oxidized Grease	161	TRIM
312	Residual Grease Film Moderately Oxidized	Good	Residual Grease Film	Cone-Spall	200	Noise
313	Residual Grease Film	Good	Residual Grease Film	Cone-Spall	181	Noise
314	Residual Grease Film Moderately Oxidized	Good	Residual Grease Film	Cone-Spall	95	TRIM
315	Residual Grease Film	Cone-Spall	Residual Grease Film	Cone-Spall	303	Time Up
316	Residual Grease Film Slightly Oxidized	Good	Residual Grease Film Slightly Oxidized	Good	207	TRIM
317	Residual Grease Film Slightly Oxidized	Good	Residual Grease Film Slightly Oxidized	Cone-Spall	310	Time Up

TABLE III
(CONTINUED)
SUMMARY OF FRONT WHEEL BEARING GREASE TESTS
POST TEST OBSERVATIONS

GROUP 3 : GREASE C

	OUTBOARD BRG. - LM12700		INBOARD BRG. - L68100			
SERIES NO.	LUBRICANT CONDITION	BEARING CONDITION	LUBRICANT CONDITION	BEARING CONDITION	HOURS RUN	REASON FOR SHUTDOWN
318	Residual Grease Film	Good	Residual Grease Film	Good	138	Test Shaft Failed
319	Residual Grease Film, Slightly Oxidized	Good	Residual Grease Film	Cup & Cone Spalled	291	Vibration
320	Residual Grease Film, greatly oxidized	Heat Discolored	Residual Grease Film	Cone Spalled	194	TRIM

TABLE IV

GROUP 4 : GREASE D

SUMMARY OF FRONT WHEEL BEARING GREASE TESTS
POST TEST OBSERVATIONS

SERIES NO.	OUTBOARD BRG. - LM12700 LUBRICANT CONDITION	OUTBOARD BRG. - LM12700 BEARING CONDITION	INBOARD BRG. - L68100 LUBRICANT CONDITION	INBOARD BRG. - L68100 BEARING CONDITION	HOURS RUN	REASON FOR SHUTDOWN
401	Residual Grease Film Slightly Oxidized	Very Good	Residual Grease Film	Good	235	Suspended
402	Residual Irreg. Grease Film -Part Oxide on Roller Path	Poor-Slight Macro Surf Spalls	Residual Grease Film	Good Mod. Glazed	59	TRIM
403	Residual Grease Film - Mod. Oxidized	Good	Residual Grease Film Part. Oxid.	Good	132	TRIM
404	Residual Grease Very Oxid.	Poor -Slight Macro Surf Spalls	Residual Grease Film	Good	321	Time Up
405	Residual Grease Film Mod. Oxid.	Poor - Minute Spalls Mod. Heat Discoloration	Residual Grease Film	Good	312	Time Up
406	Residual Grease Film Partly Oxidized	Good	Residual Grease Film Part. Oxid.	Good	306	Time Up
407	Residual Grease Film Partly Oxidized	Good	Residual Grease Film Part. Oxid.	Cup Spalled	240	Noise
408	Residual Grease Film Partly Oxid.	Poor Macrospalled	Residual Grease Film	Good	311	Time Up
409	Residual Grease Film Partly Oxid.	Poor Microspalled	Residual Grease Film	Cup Spalled	97	Noise
410	Residual Grease Film	Good	Residual Grease Film	Good	347	Time Up

TABLE IV
(CONTINUED)
SUMMARY OF FRONT WHEEL BEARING GREASE TESTS
POST TEST OBSERVATIONS

GROUP 4 : GREASE D

	OUTBOARD BRG. - LM12700		INBOARD BRG. - L68100			
SERIES NO.	LUBRICANT CONDITION	BEARING CONDITION	LUBRICANT CONDITION	BEARING CONDITION	HOURS RUN	REASON FOR SHUTDOWN
411	Residual Grease Film	Very Good	Residual Grease Film	Very Good	301	Time Up
412	Residual Grease Film	Very Good	Residual Grease Film	Good	95	Susp.
413	Residual Grease Film	Good	Residual Grease Film	Good	300	Time Up
414	Residual Grease Film	Good	Residual Grease Film	Good	301	Time Up
415	Residual Grease Film Part. Oxid.	Cone-Spalled	Residual Grease Film Part. Oxid.	Fair Microspalled	221	TRIM
416	Residual Grease Film	Good	Residual Grease Film	Good	319	Time Up
417	Residual Grease Film Part. Oxid.	Very Good	Residual Grease Film	Good	319	Time Up
418	Residual Grease Film Part. Oxid.	Fair-Trace Microspalled	Residual Grease Film	Good	300	Time Up
419	Residual Grease Film	Good	Residual Grease Film	Good	248	Susp.
420	Residual Grease Film	Good	Residual Grease Film	Good	300	Time Up

TABLE V

GROUP 5 : GREASE E

SUMMARY OF FRONT WHEEL BEARING GREASE TESTS
POST TEST OBSERVATIONS

SERIES NO.	OUTBOARD BRG. - LM12700 LUBRICANT CONDITION	OUTBOARD BRG. - LM12700 BEARING CONDITION	INBOARD BRG. - L68100 LUBRICANT CONDITION	INBOARD BRG. - L68100 BEARING CONDITION	HOURS RUN	REASON FOR SHUTDOWN
501	Residual Grease Film	Good-Cone Micro surf. distress	Residual Grease Film	Very Good	91	TRIM
502	Residual Grease Film	Excellent	Residual Grease Film	Excellent	310	Time Up
503	Residual Grease Film	Excellent	Residual Grease Film	Excellent	360	Time Up
504	Residual Grease Film	Excellent	Residual Grease Film	Excellent	300	Time UP
505	Residual Grease Film	Excellent	Residual Grease Film	Excellent	301	Time Up
506	Residual Grease Film	Excellent	Residual Grease Film	Excellent	307	Time Up
507	Residual Grease Film	Excellent	Residual Grease Film	Excellent	300	Time Up
508	Residual Grease Film	Excellent	Residual Grease Film	Excellent	300	Time Up
509	Residual Grease Film	Excellent	Residual Grease Film	Excellent	313	Time Up
510	Residual Grease Film	Good	Residual Grease Film	Excellent	303	Time Up
511	Residual Grease Film	Excellent	Residual Grease Film	Good	303	Time Up
512	Residual Grease Film	Excellent	Residual Grease Film	Good-Flaked roller	232	Noise
513	Residual Grease Film	Excellent	Residual Grease Film	Excellent	331	Time Up
514	Residual Grease Film	Excellent	Residual Grease Film	Excellent	297	Time Up
515	Residual Grease Film	Excellent	Residual Grease Film	Excellent	308	Time Up
516	Residual Grease Film	Excellent	Residual Grease Film	Good	297	Time Up
517	Residual Grease Film	Excellent	Residual Grease Film	Excellent	328	Time Up
518	Residual Grease Film	Excellent	Residual Grease Film	Excellent	305	Time Up
519	Residual Grease Film	Excellent	Residual Grease Film	Excellent	401	Time Up
520	Residual Grease Film	Excellent	Residual Grease Film	Excellent	304	Time Up

TABLE VI

GROUP 6 : GREASE F

SUMMARY OF FRONT WHEEL BEARING GREASE TESTS
POST TEST OBSERVATIONS

	OUTBOARD BRG. - LM12700		INBOARD BRG. - L68100			
SERIES NO.	LUBRICANT CONDITION	BEARING CONDITION	LUBRICANT CONDITION	BEARING CONDITION	HOURS RUN	REASON FOR SHUTDOWN
601	Dry-No Grease	Poor-Micro Surface Spalls, Lubrication Failure	Residual Grease Film-Hvy. Oxid.	Poor-Micro Surface Spalls Lubrication Failure	152	TRIM
602	Dry Residual Grease Film	Poor-Macro Surface Spalls	Residual Grease Film-Mod. Oxid.	Good	302	Time Up
603	Dry-Trace Oil	Fair	Residual Grease Film-Mod. Oxid.	Fair	312	Time Up
604	Dry Residual Grease Film	Cone Spalled	Residual Grease Film-Mod. Oxid.	Fair	312	Time Up
605	Dry Residual Grease Film	Good	Residual Grease Film-Mod. Oxid.	Cup Spalled	311	Noise
606	Dry Residual Grease Film	Cone Spalled Macro Surface Distress	Residual Grease Film-Mod. Oxid.	Roller Spalled	307	Time Up
607	Dry Residual Grease Film	Cone Minute Spall	Residual Grease Film-Mod. Oxid.	Cup Spalled	222	Noise
608	Residual Grease Film	Good	Residual Grease Film	Fair	120	Susp.
609	Dry-No Grease	Lubrication Failure	Dry-No Grease	Cone Macro Spalled Lubrication Failure	51	TRIM
610	Dry-No Grease	Poor-Macro Surface Spalled-Lubrication Failure	Dry-No Grease	Poor-Heat Discolored Lubrication Failure	295	Time Up
611	Dry-No Grease	Poor-Macro Surface Spalled-Lubrication Failure	Residual Oil Film	Good	261	TRIM

TABLE VI
(CONTINUED)

GROUP 6 : GREASE F

SUMMARY OF FRONT WHEEL BEARING GREASE TESTS
POST TEST OBSERVATIONS

SERIES NO.	OUTBOARD BRG. - LM12700		INBOARD BRG. - L68100		HOURS RUN	REASON FOR SHUTDOWN
	LUBRICANT CONDITION	BEARING CONDITION	LUBRICANT CONDITION	BEARING CONDITION		
612	Dry-No Grease	Lubrication Failure	Residual Grease Film	Good	235	TRIM
613	Dry-No Grease	Fair	Residual Grease Film	Good	298	Time Up
614	Almost Dry	Fair	Residual Grease Film	Good	308	Time Up
615	Dry	Lubricant Failure Overheated	Residual Grease	Good	308	Time Up
616	Residual Grease Film	Good	Residual Grease Film	Cone Spalled	50	Vibration
617	Residual Grease Film	Fair	Residual Grease Film	Cup Spalled	106	Vibration
618	Dry	Fair	Residual Grease Film	Cup Spalled	152	TRIM
619	Dry	Cone Spalled Several Small Areas	Residual Grease Film	Cone Microspalled	302	Time Up
620	Dry	Poor-Lubrication Failure	Residual Grease Film	Good	197	TRIM

The observations presented in the foregoing Tables I to VI are summarized as follows:

Grease A - Table I

None of the twenty bearings lubricated with Grease A achieved the preselected time up life of 300 hours of operation which represents 14.4 million revolutions. The theoretical L_{10} life of the bearing set or system is 11.2 million revolutions as explained in Appendix 1.

Most of the bearings were devoid of grease. The rolling contacts were virtually dry or retained only a light oil film. Where a slight residual grease film remained, it was moderately oxidized.

As a result of this deficiency in lubrication of the rolling contact surfaces,all of the bearings had some degree of damage. The failures ranged from large spalls which in themselves caused extensive vibration, down to microspalls which were just barely visible without optical magnification. All of the bearings had extensively microspalled areas or surface distress, and heat discoloration, a further indication of inadequate lubrication.

Grease B - Table II

None of the bearings lubricated with Grease B achieved the 300 hour time up life specified. The lubrication characteristics of Grease B, are similar to those of Grease A in that the failures appear to be lubricant related. As with Grease A, the bearings, in most instances were dry. If a thin film of residual grease remained, it was moderately oxidized.

The rolling contact surfaces of many bearings had been distress to various degrees, ranging from large spalls to microspalls, and most of the surfaces were heat discolored.

Grease C - Table III

The performance of Grease C appears to be better than Greases A or B. Twenty percent of the bearings completed the test. All the bearings retained a residual film of grease, and the rolling contacts were wet with a light film of oil.

Although the failed bearings were the result of spalled surfaces, the unfailed companion bearings in many instances were not heat discolored and appeared in good condition.

The failures again ranged from large spalls to minute surface damage exemplified by microspalls with light heat discoloration and glazing. On the whole, this group of bearings had a distinctively better appearance then the bearings lubricated with Greases A and B. On this basis, the lubrication characteristics of Grease C are apparently better.

Grease D - Table IV

More than 50% of the bearings lubricated with Grease D successfully completed the test. All of the bearings were coated with a substantial residual grease film which was slightly to moderately oxidized. This observation is tempered by the fact that most of the bearings ran almost three times longer than the bearings of the previous three groups, the greases of which showed equivalent degrees of oxidation.

The surfaces of many of the unfailed bearings appeared in good condition. The failed bearings had failures ranging from large spalls to microspalls normally associated with boundry lubrication operation. The lubrication characteristics of Grease D is adjudged to be significantly better than Greases A, B, and C.

Grease E - Table V

Approximately 90% of the bearings lubricated with Grease E completed the test successfully. All bearings were coated with a thick, black grease. Virtually, all of the bearings were in excellent condition attesting to the superiority of this lubricant.

In most instances, there was no evidence of surface distress or inadequate lubrication exhibited. Grease E apparently has superior lubrication characteristics; and is the best of the six greases evaluated.

Grease F - Table VI

About 45% of the bearings lubricated with Grease F completed the test to 300 hours. It will be recalled that none of the bearings lubricated with Greases A and B completed the test and that many of the bearings ran only one third as long. Examination of the grease remaining in the bearings lubricated with Grease F disclosed that the bearing surfaces were virtually dry of lubricant while in others, where some residual grease remained, it was moderately to heavily oxidized.

Generally, the bearings showed signs of inadequate lubrication as evidenced by the surface distress which ranged from large spalls down to microsize, and the presence of heat discoloration. The lubrication characteristics of Grease F is catagorized as being better than Greases A and B, and perhaps not as good as Grease C.

6. Data Analysis - Life Results

(a) Weibull Analysis of Bearing Data

The life data of each bearing-grease group has been statistically treated employing an SKF developed maximum likelihood computer program(1,2,&3)*. The program establishes the L_{10} and L_{50} lives and 90% confidence interval estimates for each, as well as the slope of the experimental Weibull distribution. The results of this analysis in terms of millions of revolutions are presented in Tables VII to XII and are summarized in Table XIII below:

TABLE XIII

SUMMARY OF ENDURANCE TEST RESULTS

Grease	Median Life - Million Revs L_{10}	L_{50}	Slope (Beta)
A	1.68	4.64	1.96
B	1.42	5.19	1.52
C	5.81	10.65	3.34
D	6.18	20.34	1.87
E	15.97	52.47	1.33
F	4.69	11.62	2.22

*Numbers in parenthesis refer to list of references on page 108.

TABLE VII

Test Results and Statistical Analysis
Presentation in Millions of Revolutions

GROUP NO. 1 FT. BELVOIR GREASE 'A'

LIVES x 10^6 REVS	
1.2000	4.2200
1.2900	4.6100
1.7300	4.8400
2.5400	5.2800
2.9300S	5.5200
3.6500	5.8300S
3.6900	6.3800
3.6900	7.2900
4.0800	8.3100
4.1200	10.2700S

****

		BETA 0.1957E 01
LCL L10 0.8674E 00	MED L10 0.1681E 01	UCL L10 0.2486E 01
LCL L50 0.3573E 01	MED L50 0.4637E 01	UCL L50 0.5924E 01

**** ***

Legend:

Beta - Weibull shape parameter or slope

Med L_{10} - Median bias corrected 90% reliable life

Med L_{50} - Median bias corrected 50% reliable life

LCL - Lower end of 90% confidence interval

UCL - Upper end of 90% confidence interval

TABLE VIII

Test Results and Statistical Analysis
Presentation in Millions of Revolutions

GROUP NO. 2 FT. BELVOIR GREASE 'B'

LIVES X 10^6 REVS	
0.5300	5.8000
0.6700	6.2800
0.7200	6.2800
2.3500	6.3800S
2.6400	6.6200
3.7400	7.9600
4.4600	9.1700
5.0800	11.3300
5.2300	11.7100
5.7100	14.4500

****

BETA
0.1519E 01

LCL L10	MED L10	UCL L10
0.6334E 00	0.1422E 01	0.2385E 01
LCL L50	MED L50	UCL L50
0.3718E 01	0.5188E 01	0.6885E 01

***

TABLE IX

Test Results and Statistical Analysis Presentation in Millions of Revolutions

GROUP NO. 3 — FT. BELVOIR GREASE "C"

LIVES X 10^6 REVS	
2.4500S	8.6900
4.5600	9.3100
4.6100S	9.6000
4.8900	9.9400S
6.3300S	11.3700
6.6200S	13.9600
7.7300	14.4500S
7.7300	14.4500
8.0000	14.5400
8.5400	14.8800

****

BETA
0.3335E 01

LCL L10	MED L10	UCL L10
0.3786E 01	0.5805E 01	0.7253E 01
LCL L50	MED L50	UCL L50
0.9095E 01	0.1065E 02	0.1270E 02

TABLE X

Test Results and Statistical Analysis
Presentation in Millions of Revolutions

GROUP NO. 5 — FT. BELVOIR GREASE 'D'

LIVES X10⁶ REVS	
2.8300	14.4000S
4.5600S	14.4400S
4.6600	14.4500S
6.3400	14.4500S
10.6100	14.9300
11.2800S	14.9800
11.5200	15.3100S
11.9000S	15.3100S
14.4000S	15.4100S
14.4000S	16.6600S

****

		BETA
		0.1868E 01
LCL L10	MED L10	UCL L10
0.2033E 01	0.6176E 01	0.9220E 01
LCL L50	MED L50	UCL L50
0.1379E 02	0.2034E 02	0.4571E 02

TABLE XI

Test Results and Statistical Analysis
Presentation in Millions of Revolutions

GROUP NO. 6 FT. BELVOIR GREASE 'E'

LIVES X 10^6 REVS

4.3700	14.5400S
11.1400	14.5900S
14.2600S	14.6400S
14.2600S	14.7800S
14.4000S	14.8800S
14.4000S	15.0200S
14.4000S	15.7400S
14.4500S	15.8800S
14.4700S	17.2800S
14.5400S	19.2500S

****

		BETA 0.1327E 01
LCL L10 0.5943E 00	MED L10 0.1597E 02	UCL L10 0.1226E 03
LCL L50 0.2809E 02	MED L50 0.5247E 03	UCL L50 0.2277E 39

TABLE XII

Test Results and Statistical Analysis
Presentation in Millions of Revolutions

GROUP NO. 4

FT. BELVOIR GREASE 'F'

LIVES X10^6 REVS

2.4000	14.1600S
2.4500	14.3000S
5.0900	14.4900S
5.7600	14.4900
7.2900	14.7400
7.3400	14.7800S
9.4600	14.7800
10.6600	14.9300
11.2800	14.9800
12.5300	14.9800S

****

		BETA
		0.2217E 01
LCL L10	MED L10	UCL L10
0.2523E 01	0.4694E 01	0.6581E 01
LCL L50	MED L50	UCL L50
0.9193E 01	0.1162E 02	0.1486E 02

* ****

(b) Comparison of Differences

A computerized Weibull plot of the experimental data were also completed for each bearing-grease group. Figures 3 to 7 present the plots of the individual failures versus cumulative probability for five of the test groups. The plot for Group E is not meaningful due to the small amount of failure data and is therefore not included.

The plots show no systematic departure from linearity and thus the experimental data represent Weibull distributions. This fact establishes the validity of the experimental results.

Multiple comparison hypothesis tests have been applied to these data to detect differences in the Weibull slope and the L_{10} lives of each test group. Methodology has recently been developed (4,5,&6) for conducting statistical tests for differences in endurance performance among several sets of life data under the assumption that the observations are drawn from two parameter Weibull distributions.

These significance tests are strictly applicable when: (1) each fatigue group contains an equal sample size and number of failure data and (2) the unfailed items are removed from test at the life of the longest-lived failure. These criteria are not adhered to in this instance, but the technique can still be applied to approximate the significance of the life differences.

(1) Comparison of Greases A, B, C and F Based Upon Slope Differences

The differences noted between Greases A, B, C and F were compared first since these lubricants are primarily of interest for use as wheel bearing lubricants. A comparison of all six greases is made later in this report.

For greases A, B, C and F, the number of failures are 17, 19, 14 and 15 respectively. Testing these four greases using statistical table values applicable to sample sizes of n = 20 with r = 15 failures is reasonable. The conclusions reached in this manner will be conservative.

Among these four greases, the highest estimated slope Beta value from Table XII is 3.34 (Grease C) and the lowest is 1.52 (Grease B). The ratio of these estimates 3.34/1.52 = 2.20, may be used to test whether a common slope may be assumed for the four samples. From Table 1 in [6] the 90% critical value for k = 4 groups of size n = 20 with number of failures r = 15 is:

$$\frac{\hat{\beta}_{max}}{\hat{\beta}_{min}} \qquad W_{0.90} = 2.15$$

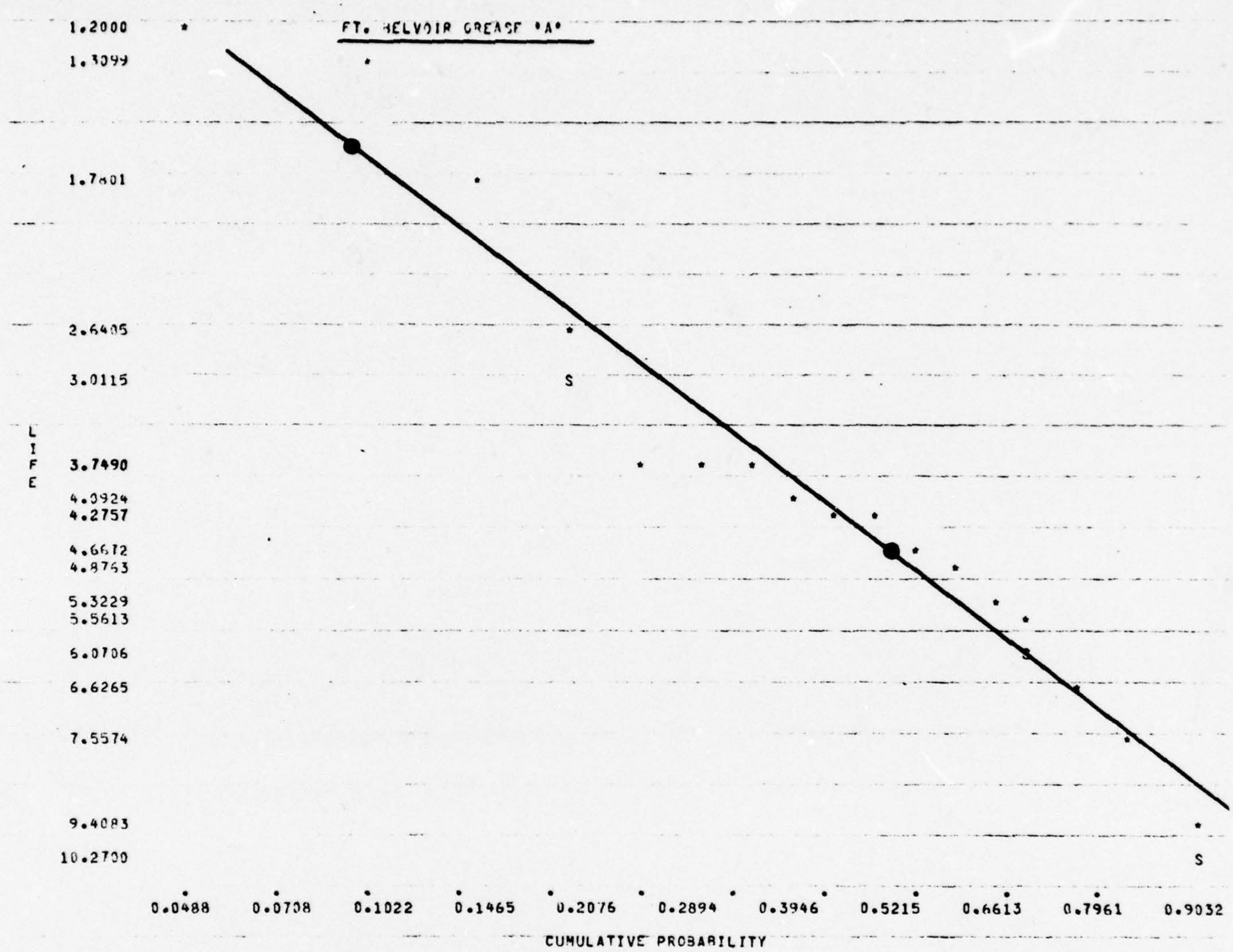


Figure 3. Weibull Plot - Grease A

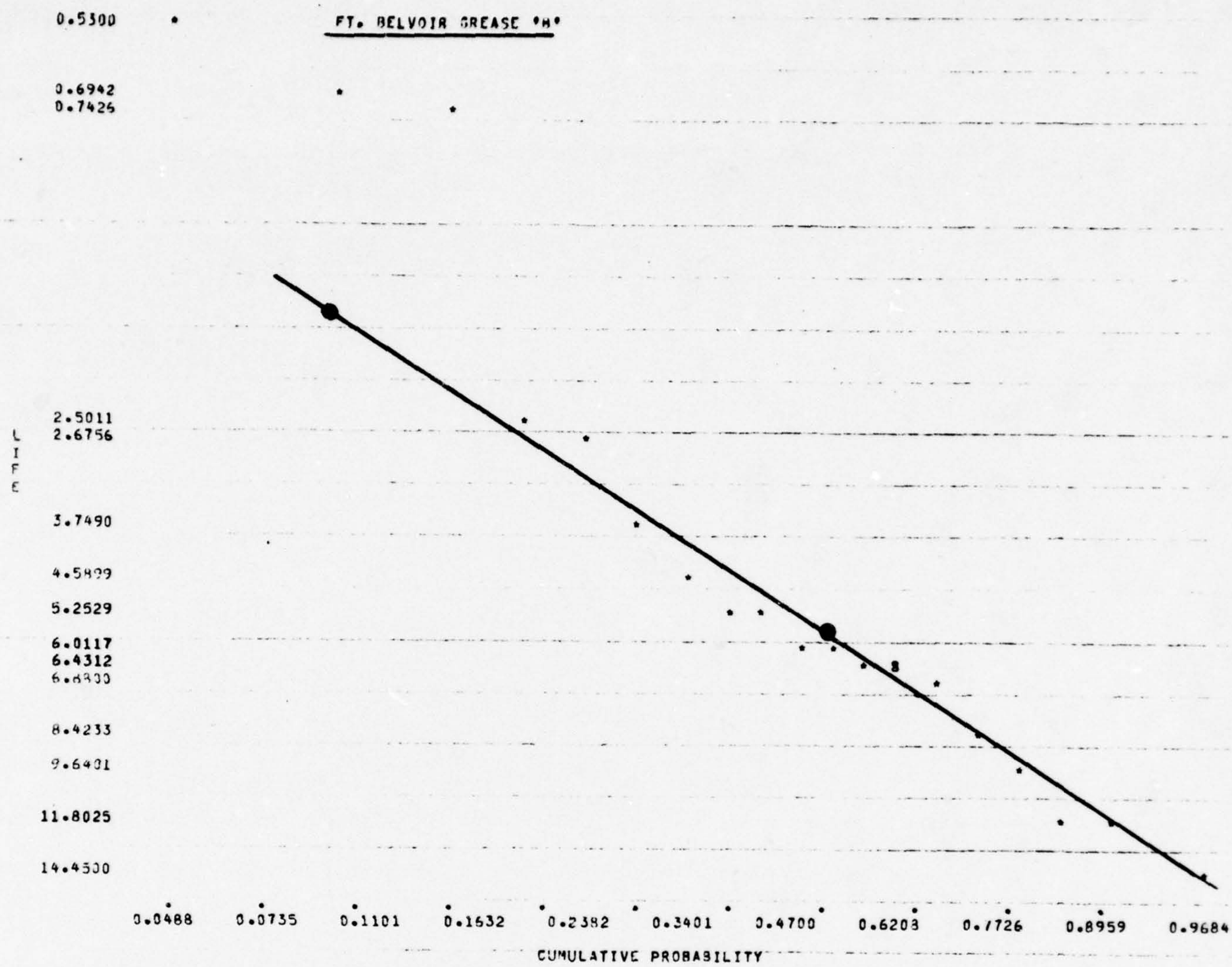


Figure 4. Weibull Plot - Grease B

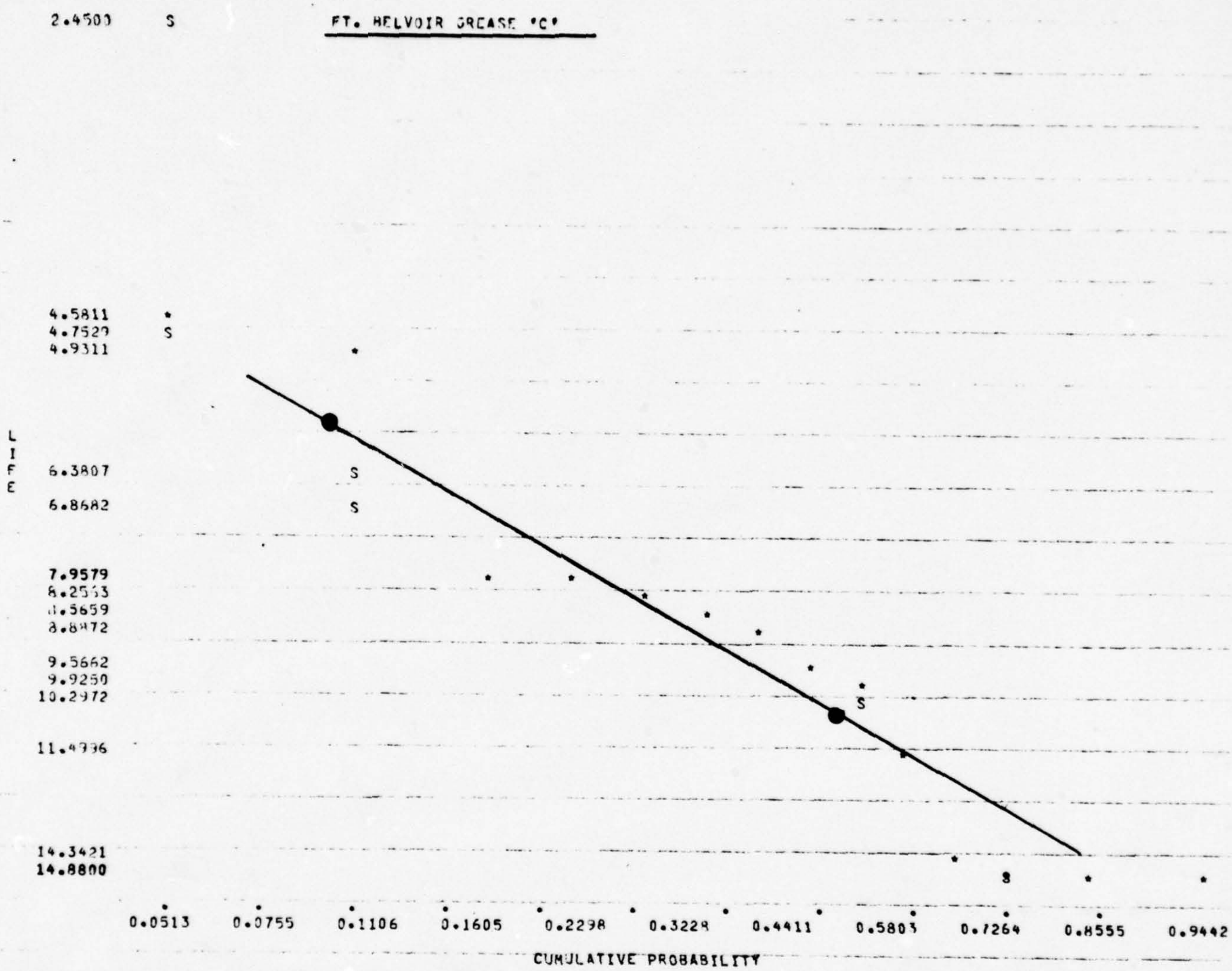


Figure 5 - Weibull Plot - Grease C

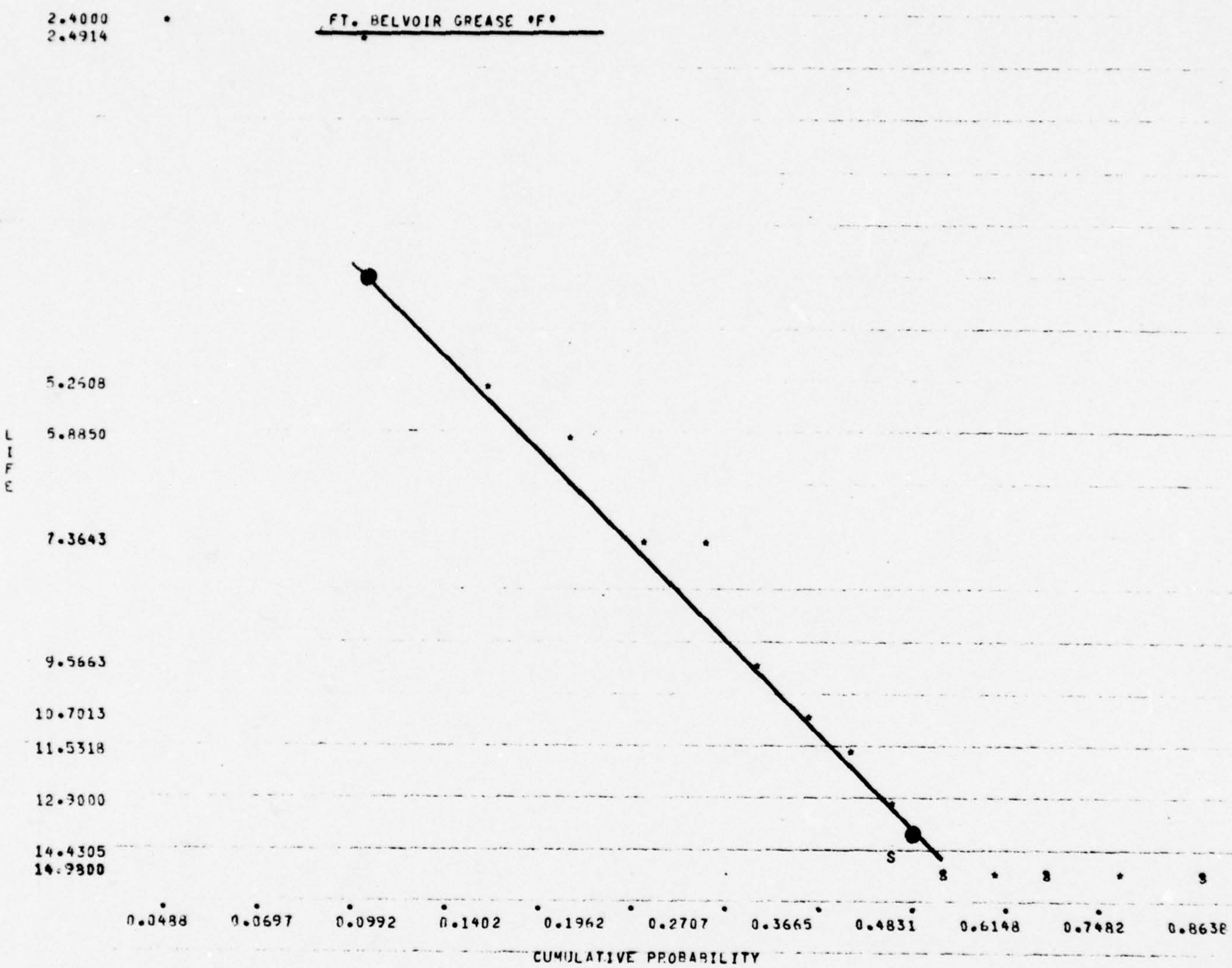


Figure 6. Weibull Plot - Grease F

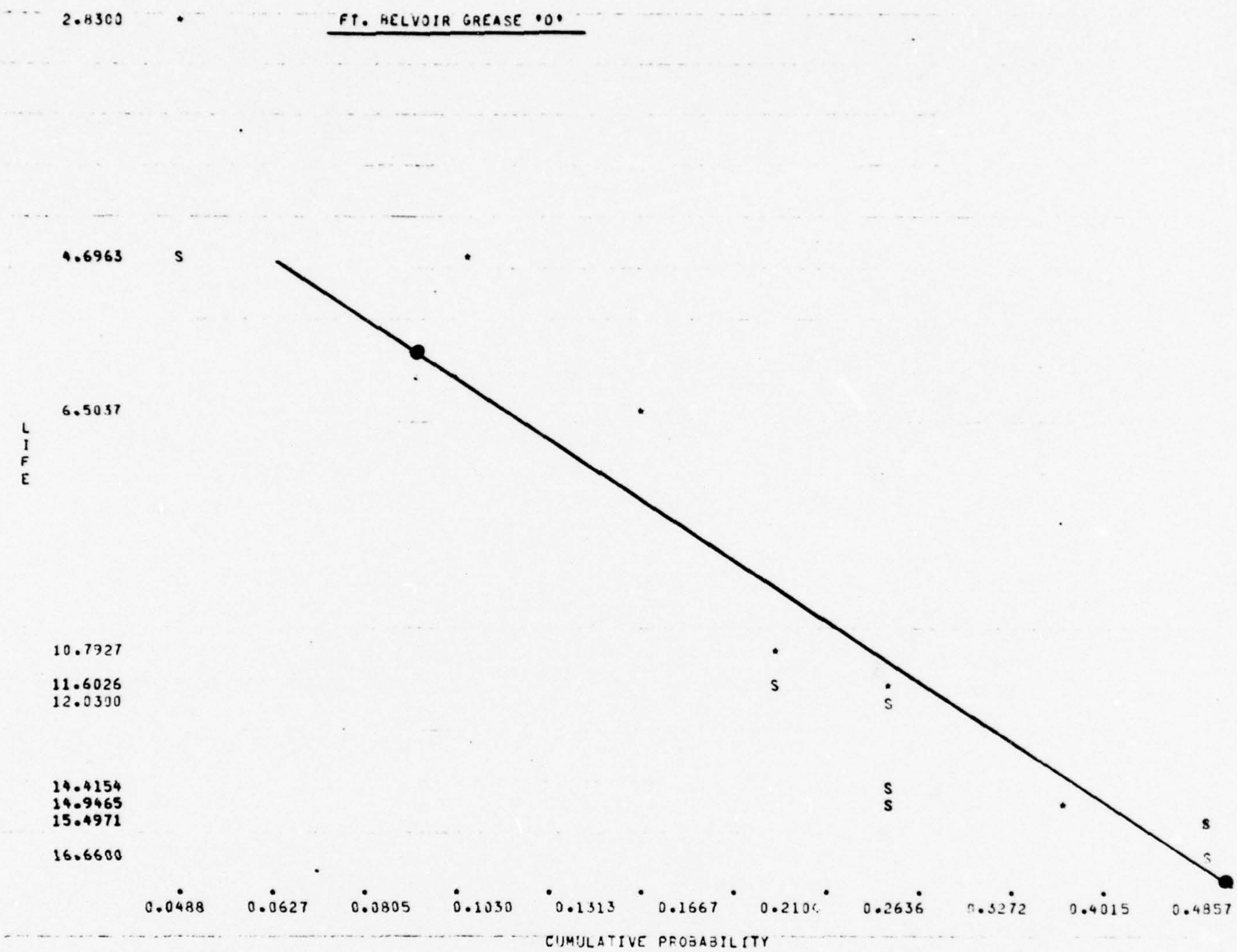


Figure 7. Weibull Plot - Grease D

Accordingly the Weibull slopes of these four groups are judged to be different. There remains to determine which are different. The ranked estimates are displayed below:

Beta	1.52	1.96	2.22	3.34
Grease	B	A	F	C

B_F/B_X	=	1.46	1.13	1	-
B_C/B_X	=	2.19	1.70	1.505	1

The greases which do not test differently from each other have been under scored by a common line. The lines indicate that either C is an outlier and B, A, and F are mutually consistent or that B is an outlier and A, F, and C are a consistant set.

Bearing experience suggests that C has an unduly high slope parameter. Grease C also has the most early suspended tests occurring at well less than the highest life of a failure. These had been diagnosed as possible failures due to an increase in temperature acceleration (TRIM). Upon inspection the bearings were found to be alright. Also one bearing was suspended when the shaft failed. This latter non conformance of the Grease C to the assumption on which the significance test is based suggests the possibility that Grease C may not truly have an aberrant slope, but may just have a high sample value due to the placement of the suspensions. In any case, we exclude Grease C, regard the slopes as homogeneous, and proceed to test for life differences among Greases A, B and F which in this study as a group are of major concern since they are basically alike chemically.

(2) Testing L_{10} Differences

From Table XIV, the slope ratio test statistic is shown to be:

$$\hat{B}(1)/\hat{B}(0) = 1.11$$

Table XIV shows the L_{10} and L_{50} estimates for Greases A, B and F, recomputed using the assumption that the experimental slopes are identical. Under this assumption, the ML estimate of the common slope is $\hat{B}(1) = 1.6125$.

TABLE XIV
Maximum Likelihood Estimate of Life Differences
Greases A, B and F

****

MAXIMUM LIKELIHOOD ESTIMATION OF 3 DATA GROUPS

	I	X0.10(I)	X0.50(I)	ETA(I)
A	1	1.3622	4.3812	5.4993
B	2	1.6700	5.3715	6.7423
F	3	3.4317	11.0377	13.8544

BETA(I),MIN= 1.5187

BETA(I),MAX= 2.2175

BETA(I),MAX/BETA(I),MIN= 1.4602

M L ESTIMATE OF SHAPE PARAMETER BETA(1)= 1.6125

M L ESTIMATE OF SHAPE PARAMETER - COMBINED DATA BETA(0)= 1.4527

SHAPE PARAMETER RATIO TEST STATISTIC BETA(1)/BETA(0)= 1.1100

LIKELIHOOD RATIO TEST STATISTIC -2LOG(LAMBDA)= 20.3533

****

From [6] the critical value for a 10% level test for $k = 3$ groups of size $n = 20$, $r = 15$ is 1.0876. There is therefore an indicated difference among the lives of Greases A, B and F.

Having determined that the lives differ, we examine in more detail how they differ. The L_{10} life estimates are:

Greases	A	B	F
$\hat{L}_{10}$	1.36	1.67	3.43
$\hat{L}_{10}F/\hat{L}_{10}x$	2.52	2.05	1
$\hat{L}_{10}B/\hat{L}_{10}x$	1.23	1	-

From tables in [6] , it is found that only with 10% probability will the quantity

$$\hat{B}_1 \ln \left(\frac{\hat{L}_{10} \text{ max.}}{\hat{L}_{10} \text{ min.}}\right)$$

exceed 0.83 for $k = 3$ groups of size $n = 20$ having $r = 15$ failures.

The least significant ratio (LSR) of L_{10} estimates based on a 10% significance level is therefore calculated from

$$\hat{B}(1) \ln (\text{LSR}) = 0.83$$

or $$\text{LSR} = \exp. \left[0.83/1.6125\right] = 1.67$$

By this criterion Grease F is seen to give a significantly higher life than A or B; and A and B are not significantly different from each other.

(3) Comparison of All Six Greases

Although we cannot perform an exact test because of the larger differences in failure numbers, it is instructive to examine all six data groups using the common slope parameter assumption. The results of this analysis are given in Table XV.

The ML estimate of the assumed common slope is $\hat{B}_{(1)} = 1.96$. The raw L_{10} estimates are quite close to the values computed using only the individual data for each group as shown below:

	$\hat{L}_{10} \times 10^6$ Revs.	
Grease	Individual Lives (Tables VII to XII)	Common Slope (From Table XV)
A	1.78	1.78
B	1.51	2.23
C	6.02	3.73
F	4.95	4.34
D	6.70	6.92
E	15.0	15.0

Using the common slope assumption results in only one reversal in the ordering of the data with Group C and F changing places. Proceeding formally we may perform the same multiple comparison analysis for all six groups as was done for groups A, B and F.

Using k = 5 in the Tables in [6] (the case k = 6 is not tabled) and conservatively, r = 5, n = 20 gives the least significant ratio:

$$LSR = \exp\left[2.233/1.96\right] = 3.12$$

TABLE XV

Maximum Likelihood Estimate of Life Differences
6 Data Group

****

MAXIMUM LIKELIHOOD ESTIMATION OF 6 DATA GROUPS

	I	X0.10(I)	X0.50(I)	ETA(I)
A	1	1.7752	4.6477	5.6048
B	2	2.2307	5.8404	7.0431
C	3	3.7322	9.7715	11.7837
F	4	4.3429	11.3706	13.7121
D	5	6.9269	18.1359	21.8707
E	6	15.0059	39.2880	47.3787

BETA(I),MIN= 1.3266

BETA(I),MAX= 3.3354

BETA(I),MAX/BETA(I),MIN= 2.5141

M L ESTIMATE OF SHAPE PARAMETER BETA(1)= 1.9573

M L ESTIMATE OF SHAPE PARAMETER - COMBINED DATA BETA(0)= 1.4186

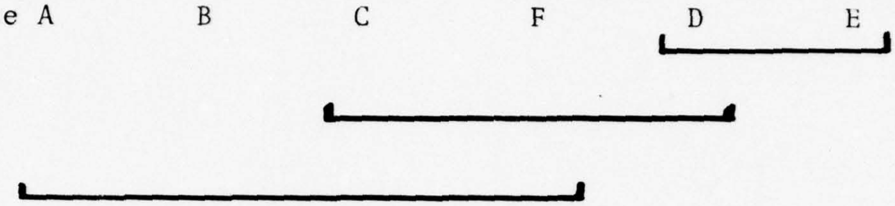
SHAPE PARAMETER RATIO TEST STATISTIC BETA(1)/BETA(0)= 1.3797

LIKELIHOOD RATIO TEST STATISTIC -2LOG(LAMBDA)= 83.0298

****

Using a common line under all pairs that fall within a ratio of 3.12 gives the following display.

$\hat{L}_{10}$ = 1.78	1.51	6.02	4.95	6.70	15.0
Grease A	B	C	F	D	E



$\hat{L}_{10}E/\hat{L}_{10}X$	8.43	6.73	4.02	3.46	2.17	1
$\hat{L}_{10}D/\hat{L}_{10}X$	3.89	3.10	1.86	1.59	1	
$\hat{L}_{10}F/\hat{L}_{10}X$	2.44	1.95	1.16	1		

Note that with this very conservative sample size assumption, the difference between Grease F, and A and B previously noted using r = 15 does not now appear. Grease E appears superior to the other four greases and Grease D is superior to Greases A and B.

On the basis of all three analysis presented, it is reasonable to assume the following.

1. The life data obtained for all greases are arranged as a two parameter Weibull distribution.
2. Grease F is better than Greases A and B.
3. Grease E is superior to all the greases evaluated.
4. Greases C and D fall in between E and F.

B. PART II - SEM OBSERVATIONS OF CONE ROLLING CONTACTS

The rolling contact surfaces of a bearing are subject to some deterioration with use. The magnitude of deterioration is dependent on a number of factors, e.g.,operating conditions, environment, and the lubrication characteristic of the grease or oil used. By keeping the major operating parameters constant, as was done in this test series, the degree of surface deterioration is then a function of the aggregate effectiveness of the grease over the total life of the bearing. The severity of distress can range from mild microwear normally associated with good lubrication to that of total exfoliation of the rolling contacts as a consequence of inadequate lubrication.

Accordingly, another important facit of this investigative program has been to assess the lubrication characteristics of these greases by observing the degree of damage to the original surface morphology after a finite time of operation.

This phase of the investigation was implimented by choosing two bearings of each size from each group of twenty bearings. In groups A, B, and C a time factor of 100 hours was chosen since the bearing lives with the first two greases were so much lower than the projected time up life of 300 hours. In groups D, E, and F a sample of unfailed bearings having completed 300 hours of operation was chosen since many of the bearings had run this length of time.

1. PROCEDURE OF EXAMINATION

Prior to examining a bearing, the residual grease was carefully removed and subjected to microanalysis. The details of this analysis are presented and discussed in Part III of this report.

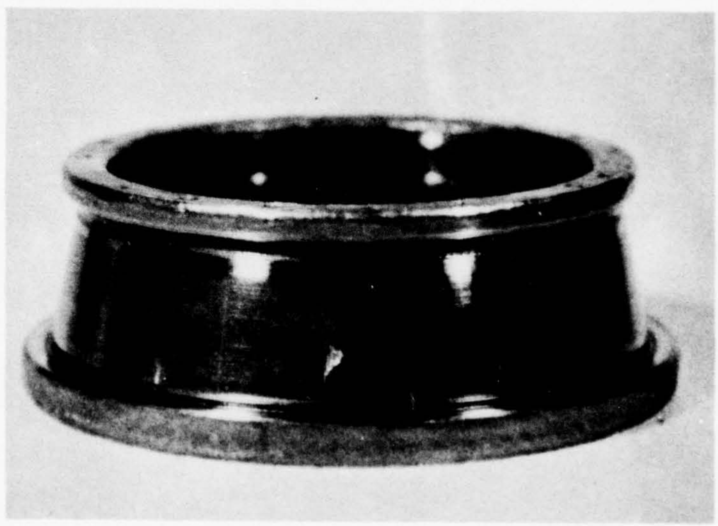
After the grease was removed and the bearing hardware degreased, a bearing was examined optically at magnifications of up to 30X for evidence of surface distress. On the basis of this examination, certain areas on the rolling contact surfaces of each cone were chosen and marked for further examination. Because the degree of damage or alteration to the surfaces was so minute, further examination required the use of higher magnification than that available by optical means. In addition, a means of micrographic documentation of these surfaces was necessary to facilitate a comparison at a later time. This was accomplished by means of an ETEC Model J Scanning Electron Microscope (SEM). Two areas were examined at magnifications of 250X and 1000X on each cone surface which exemplified the condition of the rolling contacts on these particular bearing samples. The first area showed the least amount of surface deterioration and was used to assess the magnitude of microwear which had occurred after a certain time interval of operation. The second area represented the maximum deterioration present. The two micrographs provide a pictorial representation of the condition of the vital running surfaces and enable a comparison of the anti-wear and lubrication characteristics of the greases being evaluated.

The reader is cautioned to view the micrographs with care. The surface defects appear in great contrast and magnitude; and, therefore are more pronounced than when viewed optically. It is noted that most of these bearings appeared to be in good condition and could have run longer before failing. Except for the obvious failures due to a spall, an auto mechanic would probably not have removed these bearings from service, on the basis of their appearance. For further reference on the techniques of examining bearing surfaces with the SEM, a definative text has been published which provides many sample scanning electron photomicrographs and discussions of failure types and progression [7].

The degree of microwear occurring on a new bearing surface can be qualitatively estimated by comparing the SEM micrographs of the run surface with the new surface . Generally, if many lines remain the microwear is considered minimal or slight. As the wear process progresses, the lines become less distinct; but as long as some lines are evident the microwear can be considered as being within acceptable limits. When the lines are obliterated, the wear may be significant, and the internal geometry detrimentally altered. A microspalled surface will eventually generate the exfoliation of larger areas which will ultimately result in the total failure of the bearing surface as shown in Figure 8.

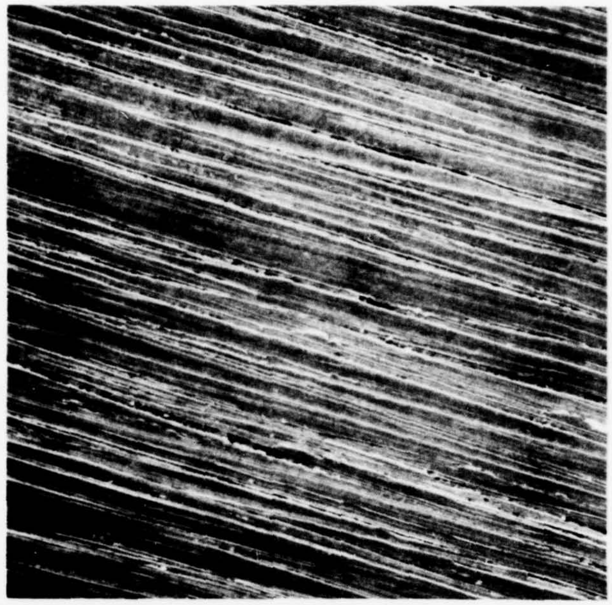
Figure 9 shows SEM micrographs of the rolling contact surfaces of a new cone at 250X and 1000X. The micrographs depict the morphological aspect of a ground and honed surface according to current manufacturing practice. The majority of the marks or lines are those produced during the grinding process. The high asperities normally associated with a ground surface have been removed by honing. Superimposed lines running at a slight angle to the grinding lines are those produced by honing. Although at this high magnification, the surfaces appear rough, in reality, the roughness is less than 8 micro-inches A.A.

Cone Surface - Macrosurface Distress
Bearing No. 305B

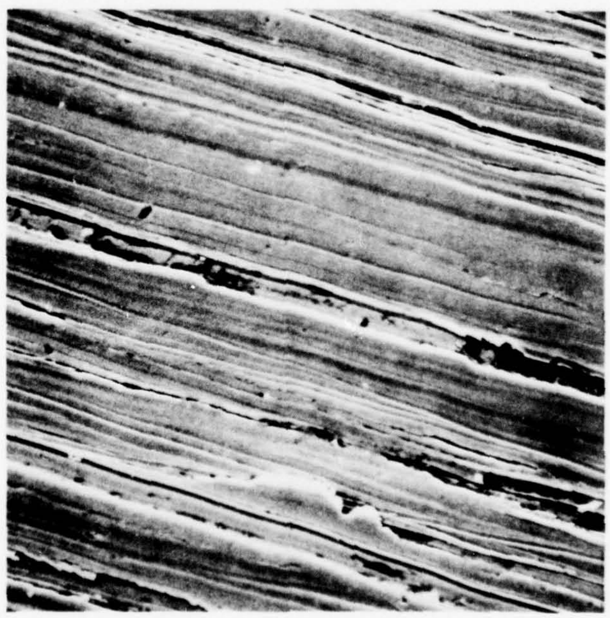


Cone Surface - Spall and
Macrosurface Distress
Bearing No. 308B

Figure 8 - Examples of Visible Damage to Cone Rolling Contact Surfaces



Magnification - 250X



Magnification - 1000X

Figure 9 - Rolling Contact Surface of New Cone

2. SEM Micrographs of Typical Bearing Surfaces

The following section describes the condition of typical cone surfaces which visually appear in good condition. Two sets of bearings lubricated with each grease have been examined. The surface damage recorded by the SEM, if any, is that which has occurred after a stipulated number of hours. Details of the visual examination are referred to in Tables I to VI.

Each figure presents SEM photomicrographs of an area having minimal damage or wear, as examined optically up to 30X magnification; and of a second area which represents the surface distress generally characteristic of that bearing. In each case, SEM photomicrographs are presented of each surface at magnifications of 250X and 1000X.

The distressed areas appear greatly exaggerated as to the nature of the damage because of the high magnifications. Generally, the microspalls found by the SEM are barely visible by optical means; the macrospalls are evident at low power (30X), and the larger spalls are barely visible to the unaided eye.

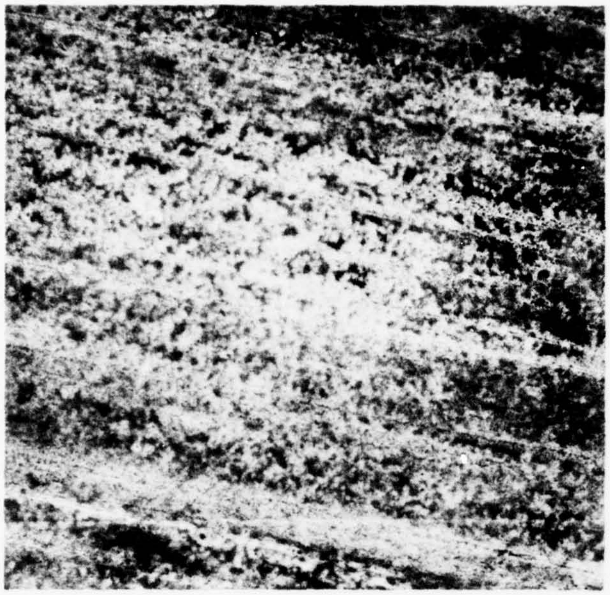
Observations, as to the condition of the bearings lubricated by each of the six greases are as follows:

GREASE A

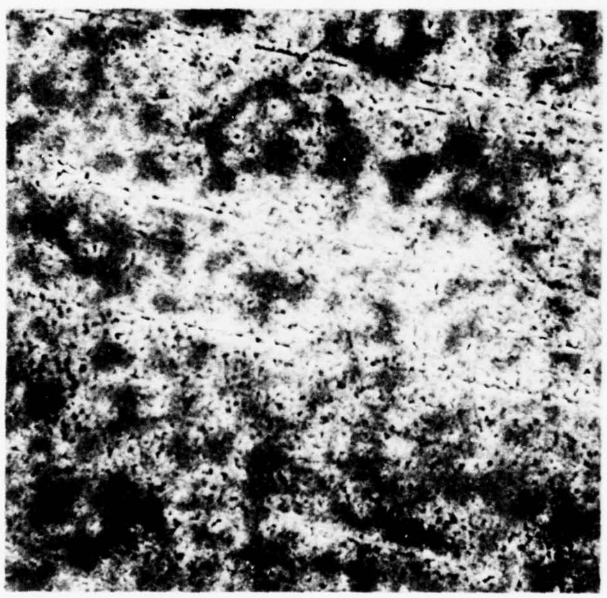
The four bearings lubricated with Grease A which were chosen for further examinations by SEM technique have various stages of surface deterioration, after only approximately 100 hours of operation. As shown in Figures 10 to 13, the grinding lines are barely visible or are almost eliminated, thereby indicating moderate to heavy wear of the rolling contacts. In addition, many of the surfaces are microspalled, and in some instances have minute spalls which are visible. There is also evidence of moderate to severe glazing.

The evidence of surface damage to the rolling contacts on these four bearings, supports the observations made on the majority of the bearings in Group 1. From these observations, it is apparent that the bearing failures have been caused by inadequate lubrication.

AREA #1



Magnification - 250X



Magnification - 1000X

AREA #2

Magnification - 250X

Magnification - 1000X

OUTBOARD BEARING LM12700

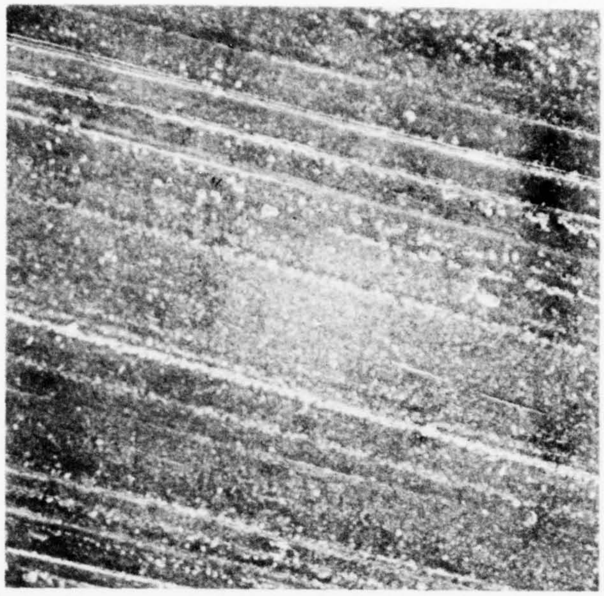
TEST BEARING NO. 103A

HOURS RUN 101

TEST LUBRICANT GREASE A

FIGURE 10 . POST TEST CONDITION OF TEST BEARINGS.

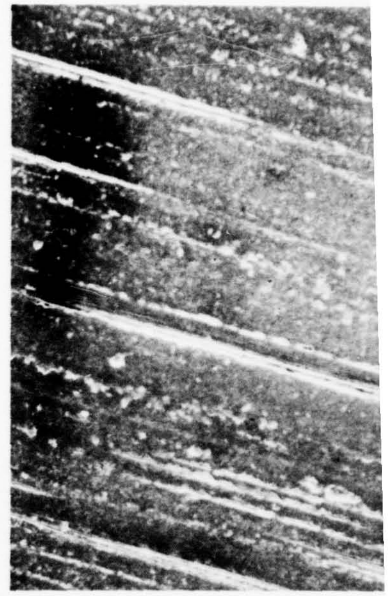
AREA #1



Magnification - 250X

Magnification - 1000X

AREA #2



Magnification - 250

Magnification - 1

OUTBOARD BEARING LM12700

TEST BEARING NO. 104A

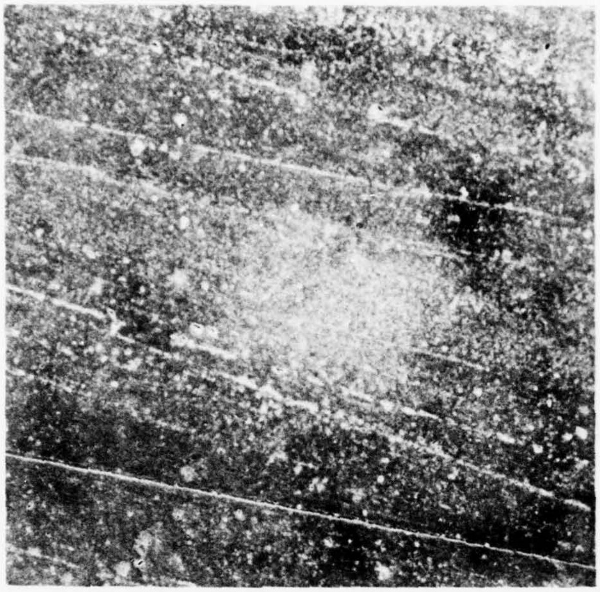
HOURS RUN 129

TEST LUBRICANT GREASE A

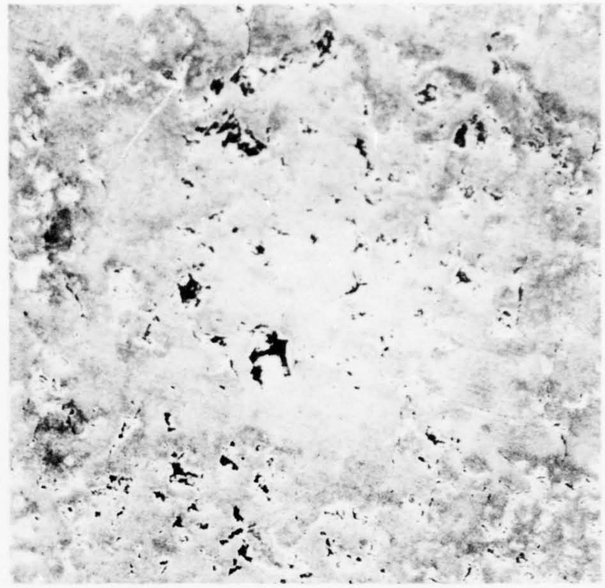
FIGURE 11 . POST TEST CONDITION OF TEST BEARINGS.

AREA #1

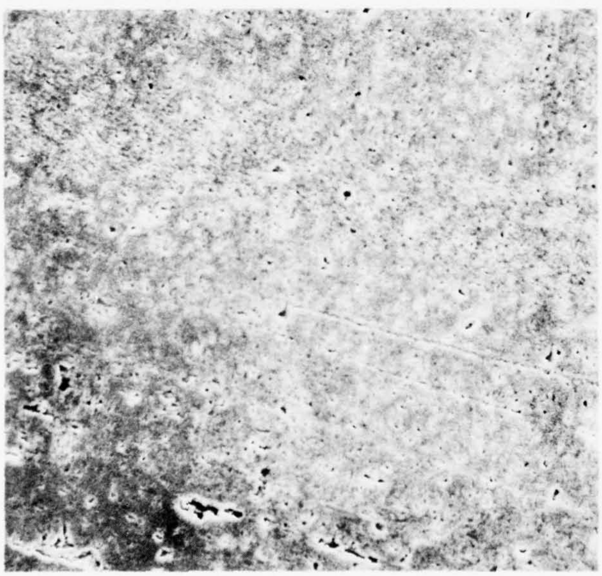
AREA #2



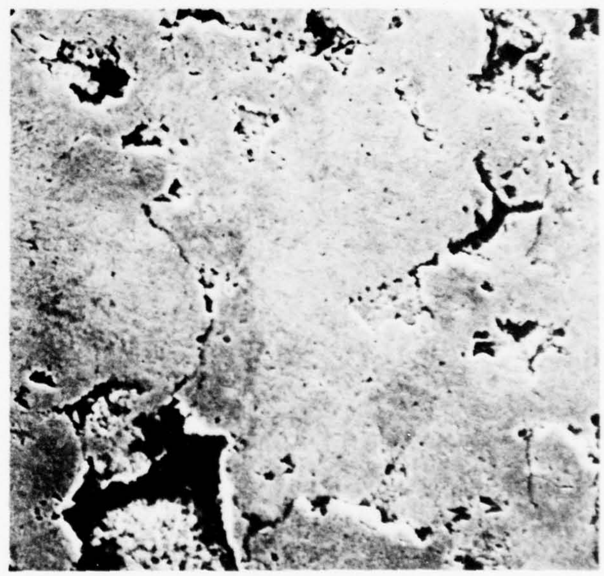
Magnification - 250X



Magnification - 250X



Magnification - 1000X



Magnification - 1000X

INBOARD BEARING L68100

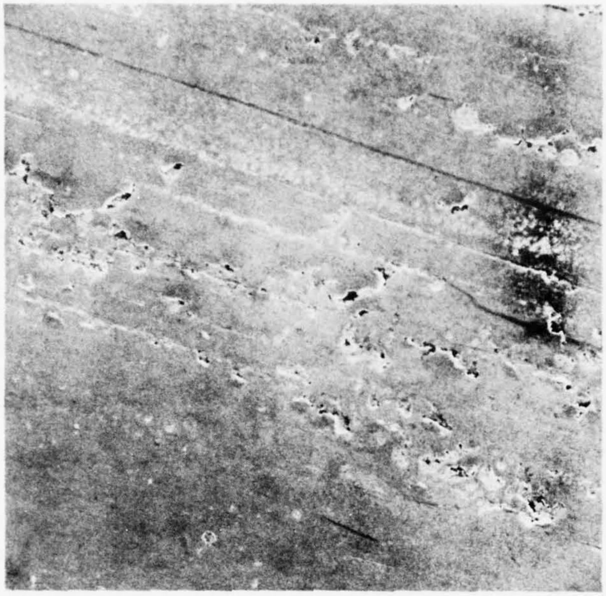
TEST BEARING 104B

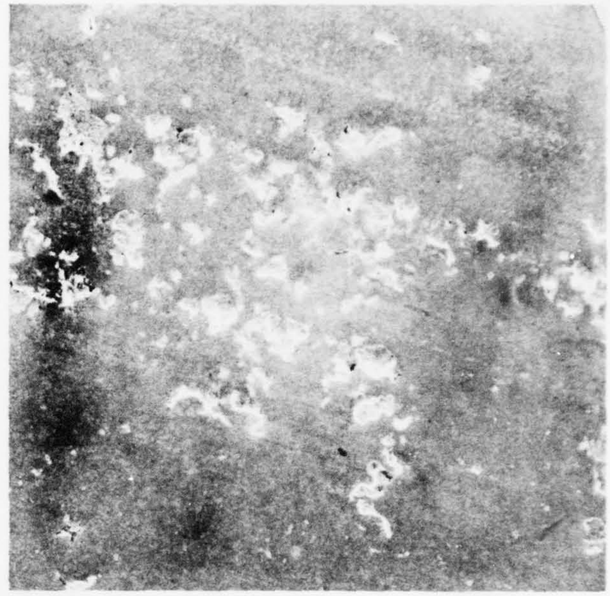
HOURS RUN 129

TEST LUBRICANT GREASE A

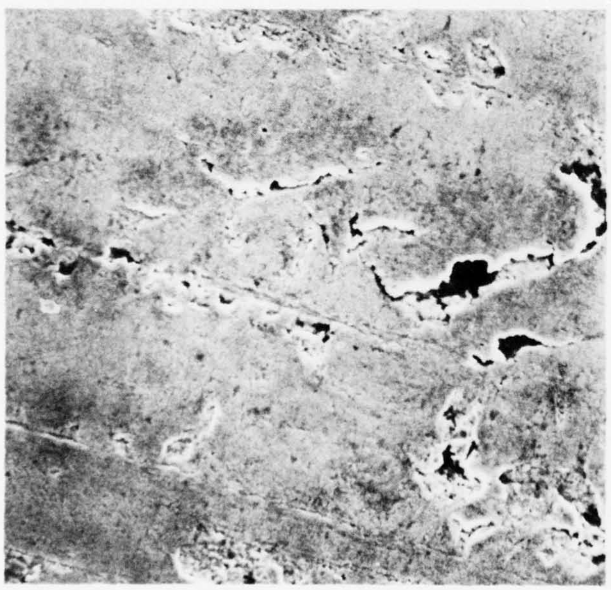
FIGURE 12 . POST TEST CONDITION OF TEST BEARINGS.

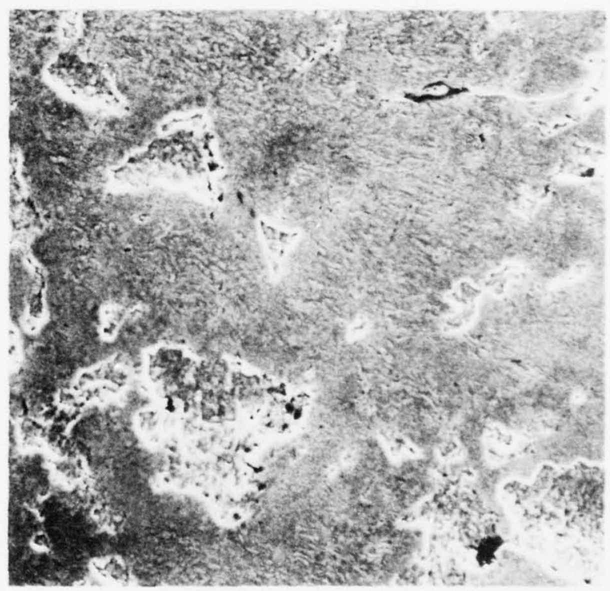
AREA #1 AREA #2





Magnification - 250X Magnification - 250X





Magnification - 1000X Magnification - 1000X

INBOARD BEARING L68100

TEST BEARING 114B

HOURS RUN 86

TEST LUBRICANT GREASE A

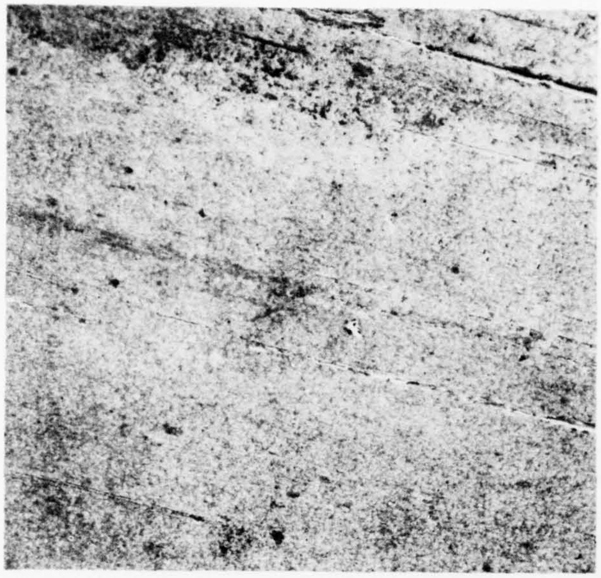
FIGURE 13 . POST TEST CONDITION OF TEST BEARINGS.

GREASE B

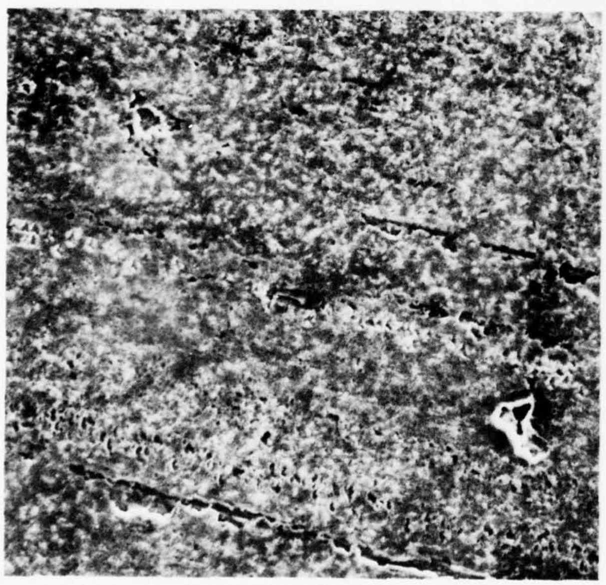
Figures 14 to 17 show the rolling contacts of cone surfaces lubricated with Grease B. As indicated, very few of the grinding lines remain, and in some instances, none remain after approximately 100 hours operation. The surface damage observed virtually duplicates that previously noted with Grease A. Most surfaces are microspalled. Some macrospalls are visible without magnification. The rolling contacts are moderately to heavily worn and are extensively glazed.

The surface damage observed supports that previously noted on the other bearings in Group 2; and it is apparent that the condition has been caused by inadequate lubrication.

AREA #1

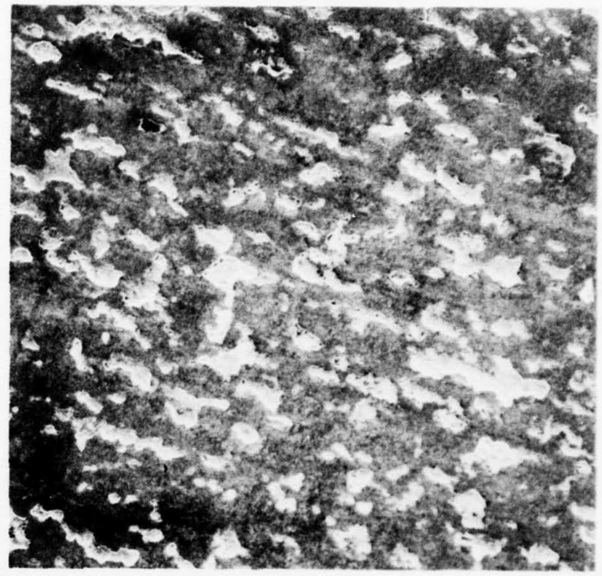


Magnification - 250X

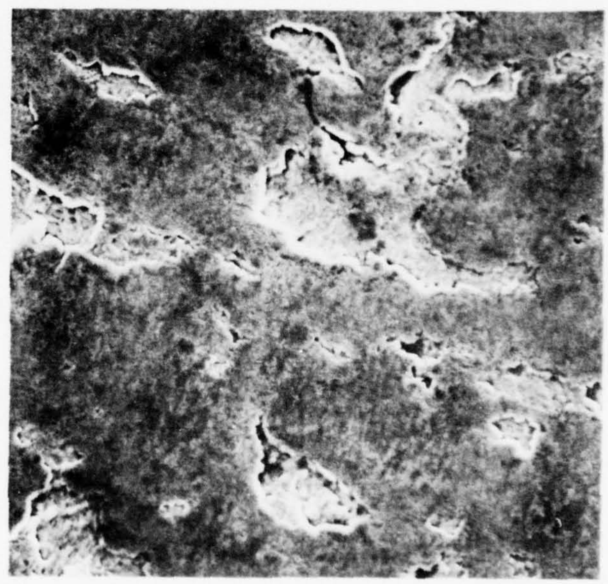


Magnification - 1000X

AREA #2



Magnification - 250X



Magnification - 1000X

OUTBOARD BEARING LM12700

TEST BEARING NO. 204A

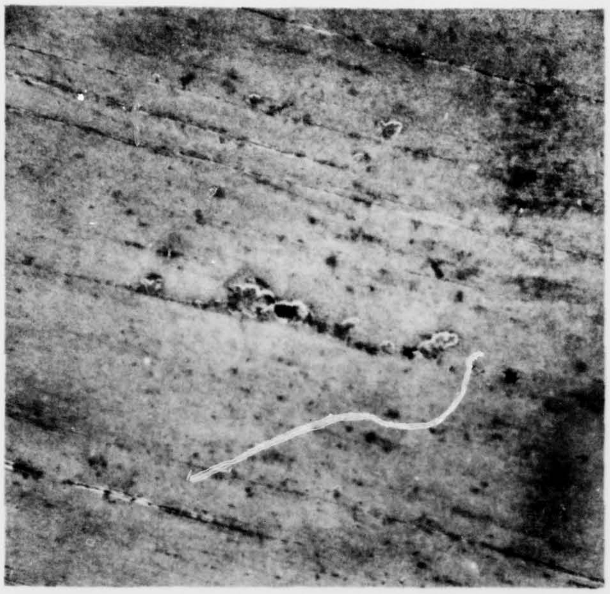
HOURS RUN 131

TEST LUBRICANT GREASE B

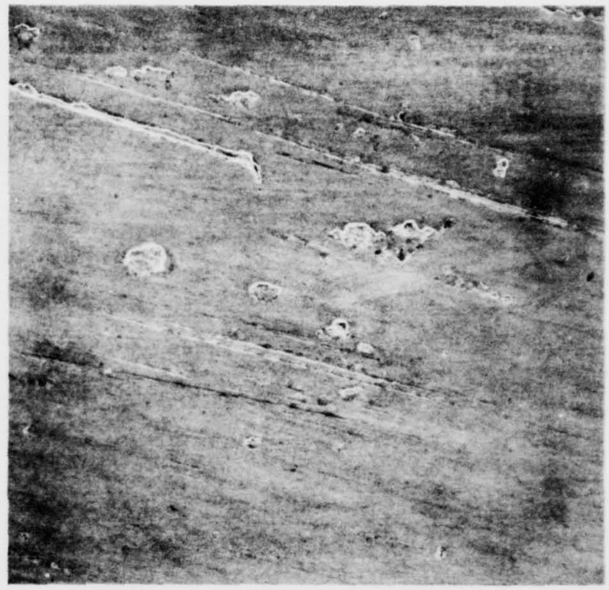
FIGURE 14. POST TEST CONDITION OF TEST BEARINGS.

AREA #1

AREA #2



Magnification - 250X



Magnification - 250X

Magnification - 1000X

Magnification - 1000X

OUTBOARD BEARING LM12700

TEST BEARING NO. 206A

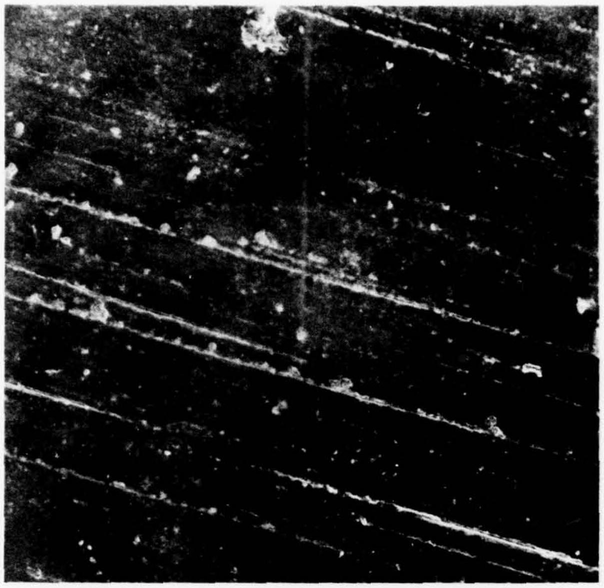
HOURS RUN 119

TEST LUBRICANT GREASE B

FIGURE 15. POST TEST CONDITION OF TEST BEARINGS.

AREA #1

AREA #2



Magnification - 250X

Magnification - 250X

Magnification - 1000X

Magnification - 1000X

INBOARD BEARING L68100

TEST BEARING 203B

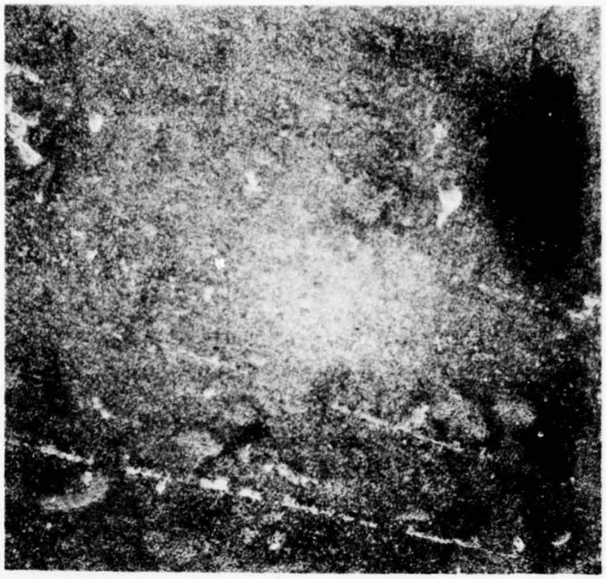
HOURS RUN 106

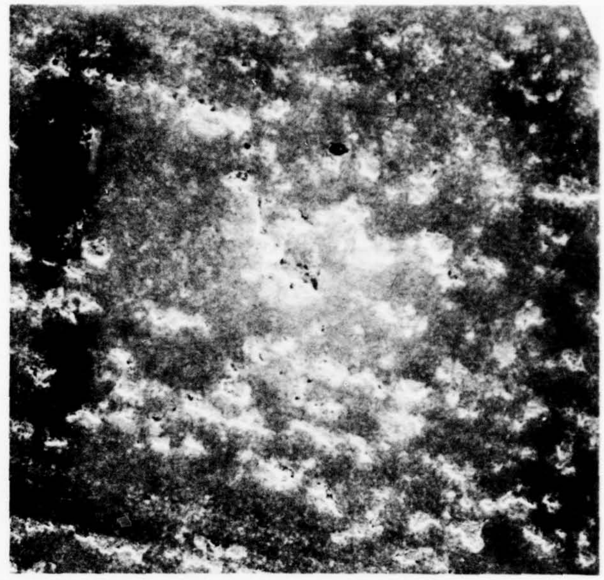
TEST LUBRICANT GREASE B

FIGURE 16 . POST TEST CONDITION OF TEST BEARINGS.

AREA #1

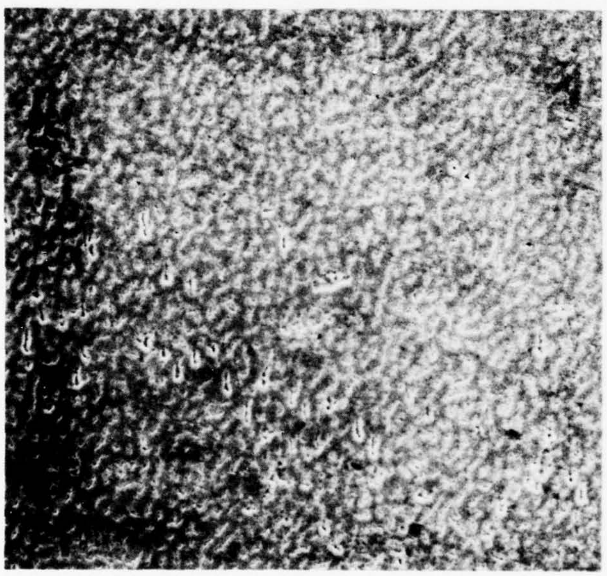
AREA #2

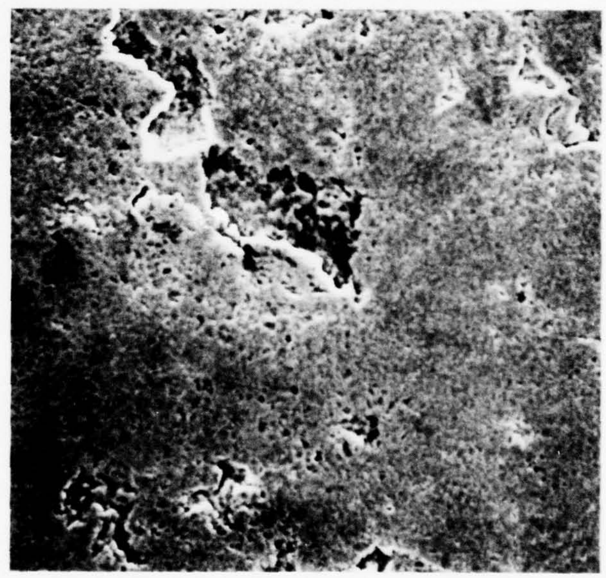




Magnification - 250X

Magnification - 250X





Magnification - 1000X

Magnification - 1000X

INBOARD BEARING L68100

TEST BEARING 220B

HOURS RUN 109

TEST LUBRICANT GREASE B

FIGURE 17 . POST TEST CONDITION OF TEST BEARINGS.

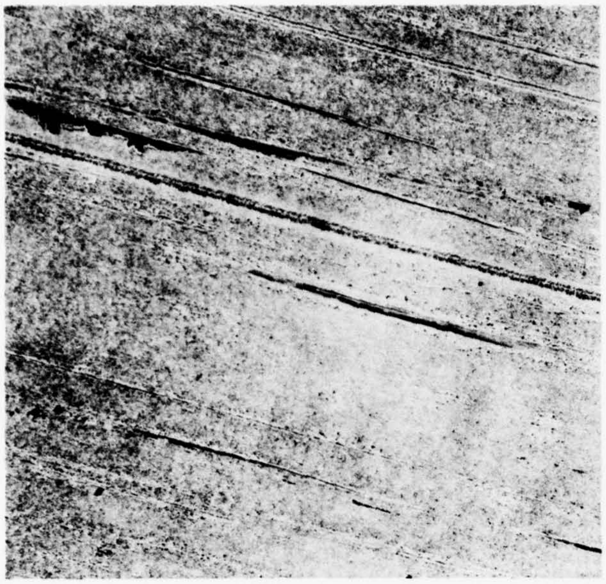
GREASE C

Figures 18 to 24 depict typical examples of cone surfaces lubricated with Grease C. Except for Bearing No. 305B, Figure 20 which ran 167 hours, these bearings completed approximately 100 hours of operation. A few grinding lines are still evident, thereby indicating that a moderate amount of wear has occurred. The surfaces are severely microspalled; and macro-spalls are visible in some areas. Glazing is light to moderate.

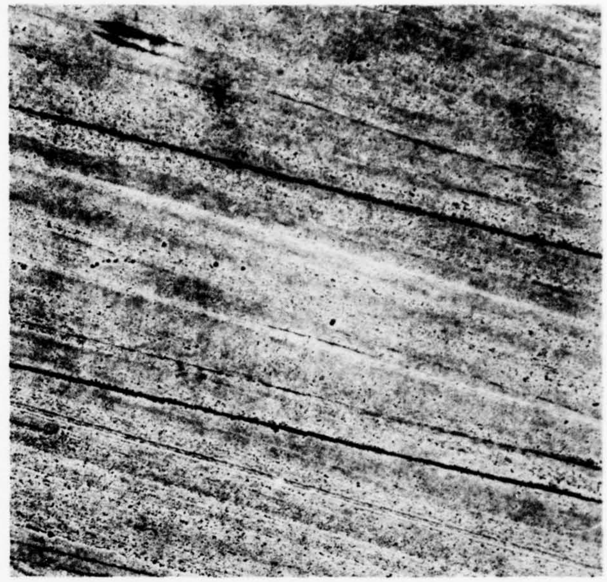
The condition of these four bearings duplicates that observed in the remaining bearings of Group 3. The damaged surfaces are characteristic of those which have operated with deficient lubrication.

AREA #1

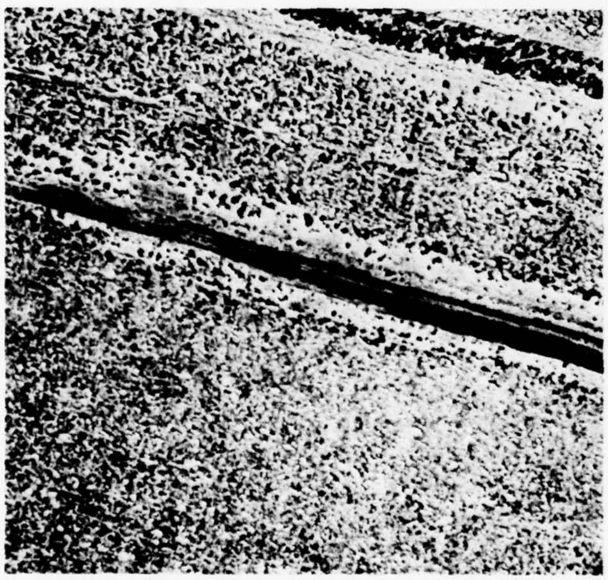
AREA #2



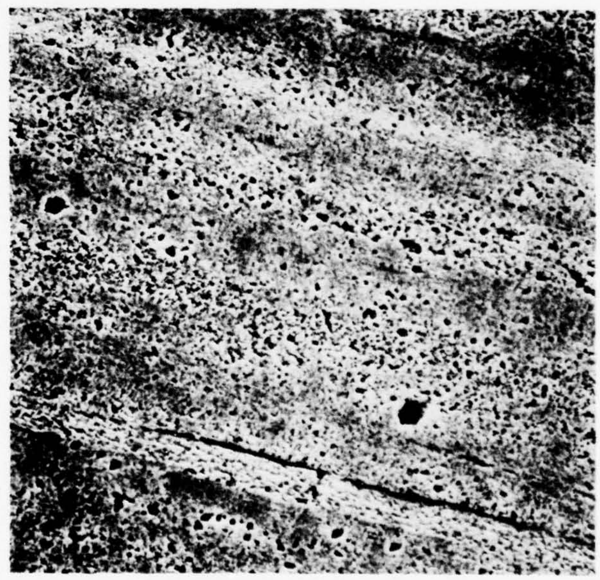
Magnification - 250X



Magnification - 250X



Magnification - 1000X



Magnification - 1000X

OUTBOARD BEARING LM12700

TEST BEARING NO. 301A

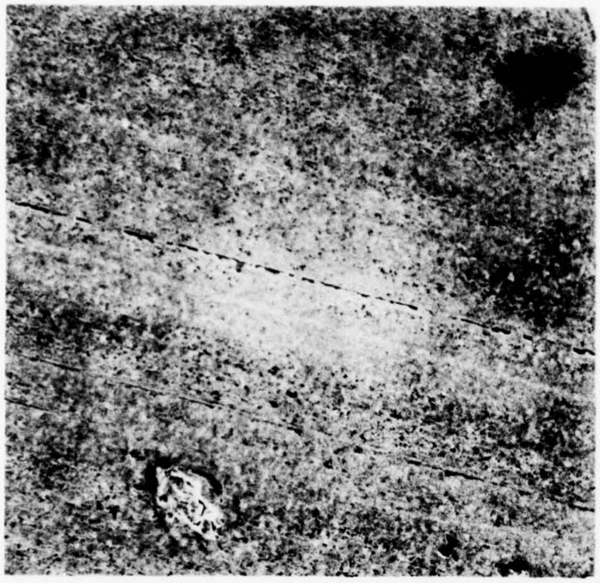
HOURS RUN 102

TEST LUBRICANT GREASE C

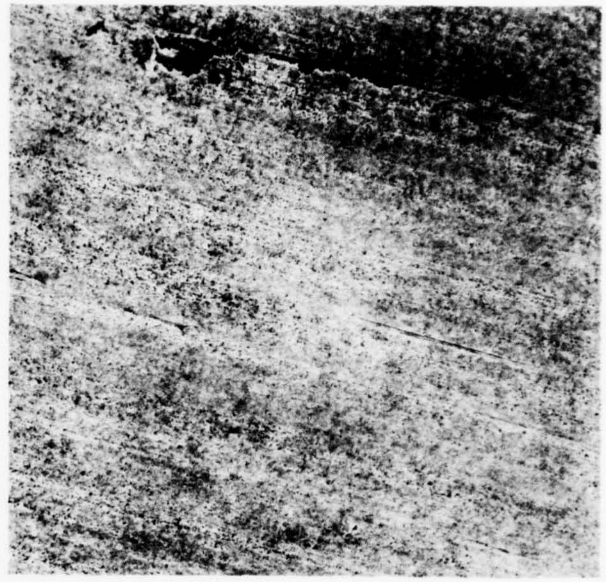
FIGURE 18. POST TEST CONDITION OF TEST BEARINGS.

AREA #1

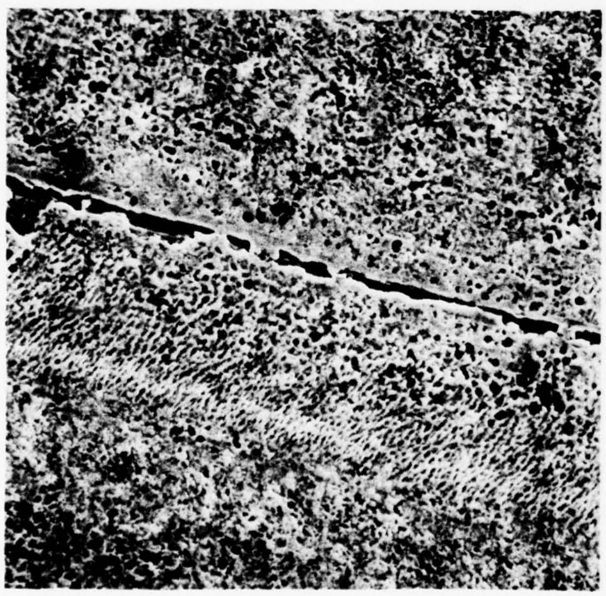
AREA #2



Magnification - 250X



Magnification - 250X



Magnification - 1000X

Magnification - 1000X

OUTBOARD BEARING LM12700

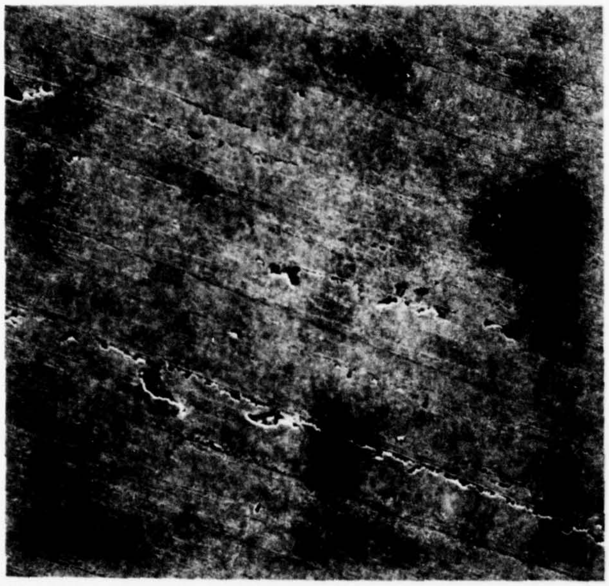
TEST BEARING NO. 309A

HOURS RUN 96

TEST LUBRICANT GREASE C

FIGURE 19. POST TEST CONDITION OF TEST BEARINGS.

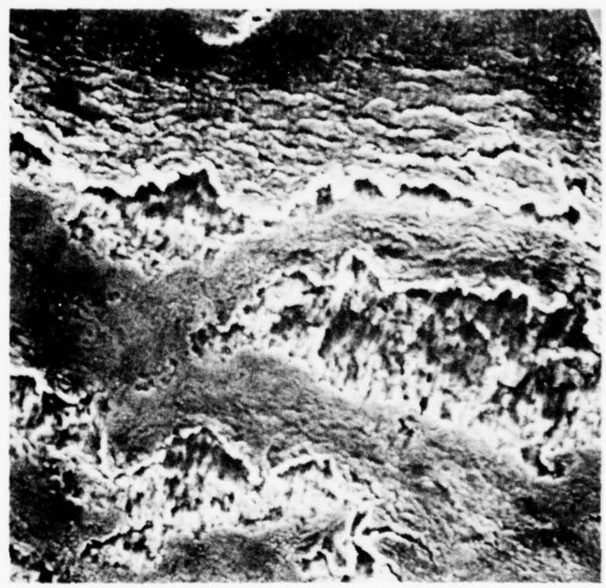
AREA #1 AREA #2



Magnification - 250X

Magnification - 250X

Magnification - 1000X



Magnification - 1000X

INBOARD BEARING L68100

TEST BEARING 305B

HOURS RUN 167

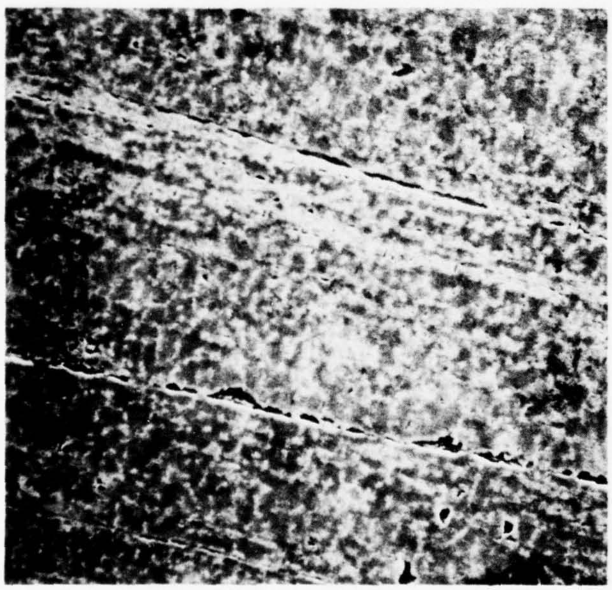
TEST LUBRICANT GREASE C

FIGURE 20 . POST TEST CONDITION OF TEST BEARINGS.

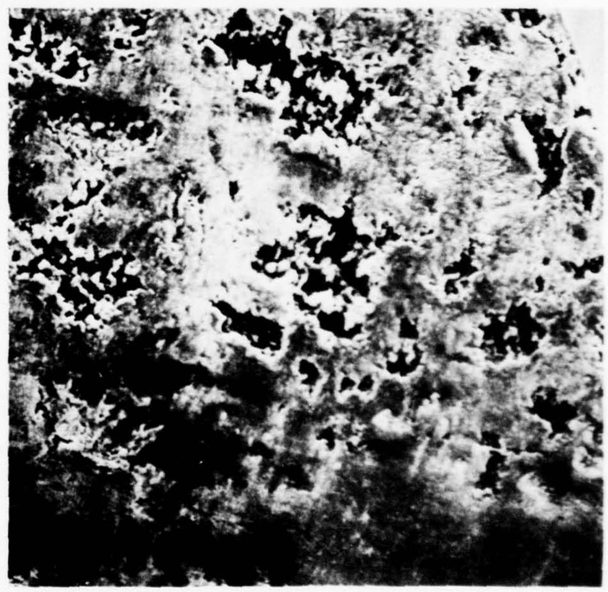
AREA #1 AREA #2

Magnification - 250X

Magnification - 250X



Magnification - 1000X



Magnification - 1000X

INBOARD BEARING L68100

TEST BEARING 309B

HOURS RUN 96

TEST LUBRICANT GREASE C

FIGURE 21 . POST TEST CONDITION OF TEST BEARINGS.

Many of the bearings lubricated with Greases D, E and F ran 300 hours, at which time the test was terminated. Consequently, SEM observations have been made on representative bearings having completed the test successfully and visibly still appear to be in good condition.

GREASE D

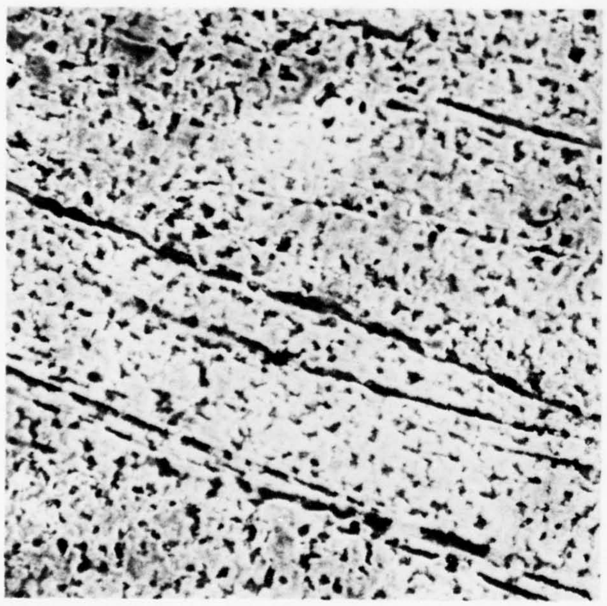
Figures 22 to 25 show micrographs of cone surfaces lubricated with Grease D after 300 hours of operation. More grinding lines are evident indicating that the wear is light to moderate. In general, the surfaces are extensively microspalled or perhaps micropitted from some corrosive agent. Some macrospalls occur in a localized area of Bearing No. 420B, Figure 19. All bearings are slightly to moderately glazed.

The surface damage observed is considered as being much less than that previously noted with Greases A, B, and C especially when one considers the time differential i.e., 100 hours as compared to 300 hours of operation.

AREA #1 AREA #2

Magnification - 250X

Magnification - 250X



Magnification - 1000X

Magnification - 1000X

OUTBOARD BEARING LM12700

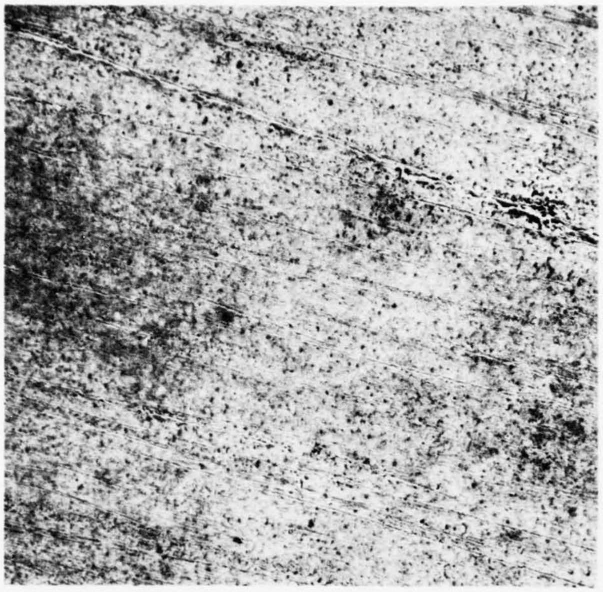
TEST BEARING NO. 406A

HOURS RUN 306

TEST LUBRICANT GREASE D

FIGURE 22 . POST TEST CONDITION OF TEST BEARINGS.

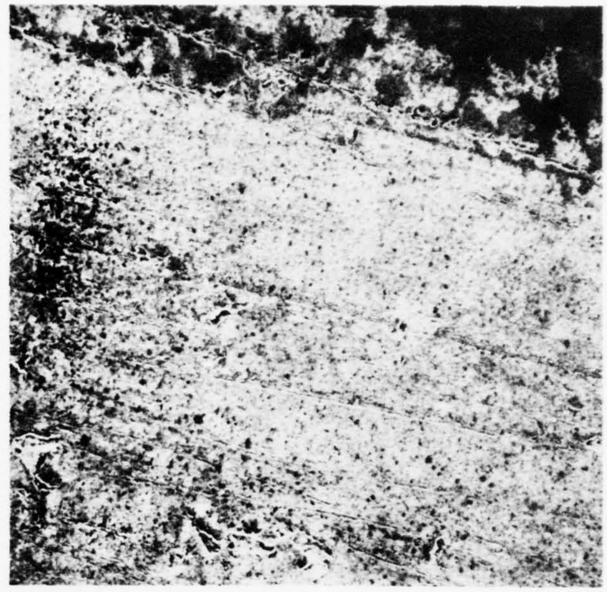
AREA #1



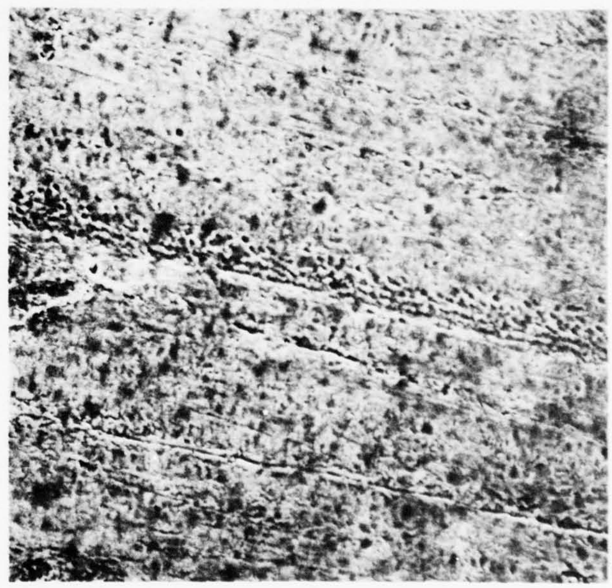
Magnification - 250X

Magnification - 1000X

AREA #2



Magnification - 250X



Magnification - 1000X

OUTBOARD BEARING LM12700

TEST BEARING NO. 420A

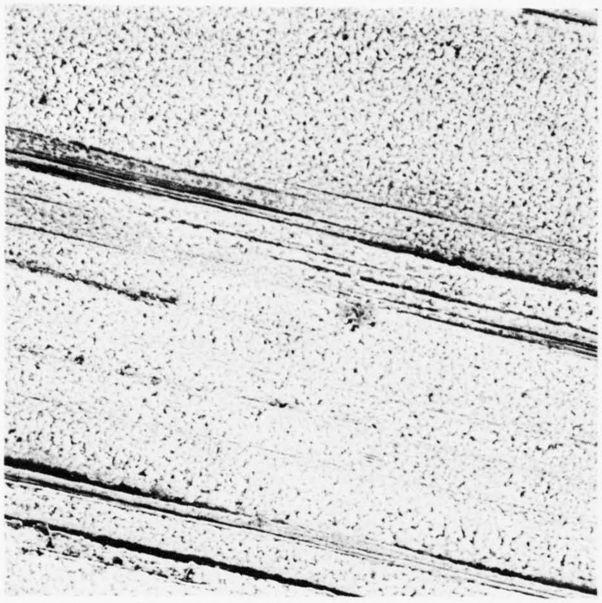
HOURS RUN 300

TEST LUBRICANT GREASE D

FIGURE 23 . POST TEST CONDITION OF TEST BEARINGS.

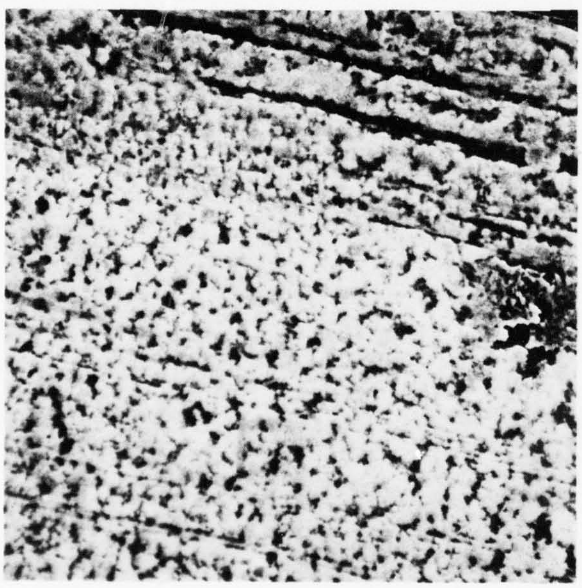
AREA #1

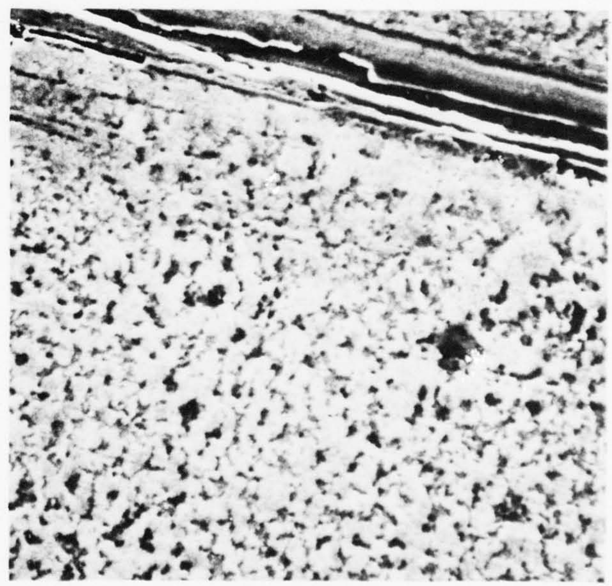
AREA #2



Magnification - 250X

Magnification - 250X





Magnification - 1000X

Magnification - 1000X

INBOARD BEARING L68100

TEST BEARING 406B

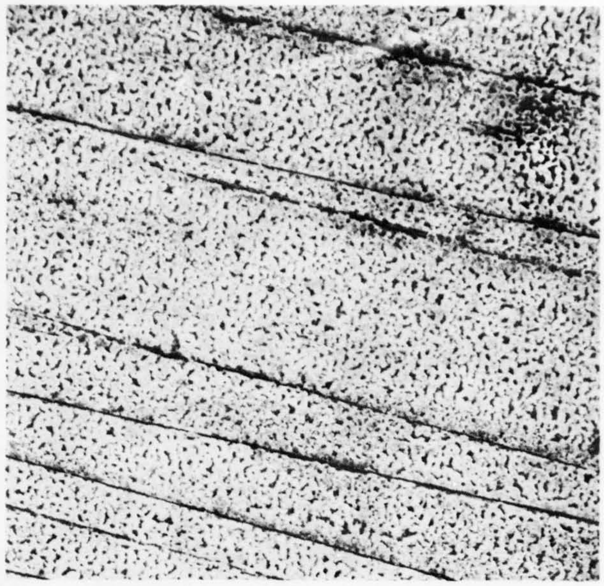
HOURS RUN 306

TEST LUBRICANT GREASE D

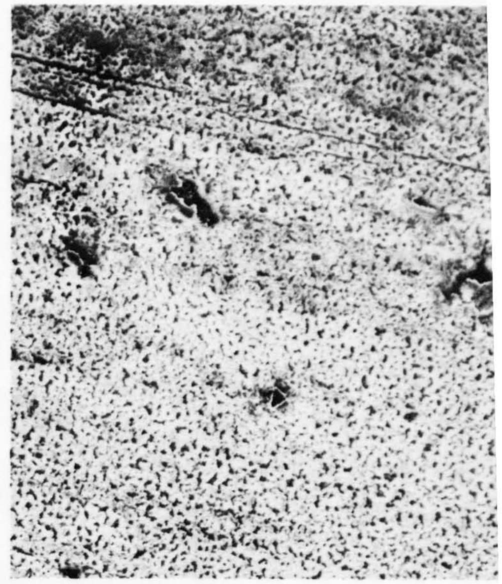
FIGURE 24 . POST TEST CONDITION OF TEST BEARINGS.

AREA #1

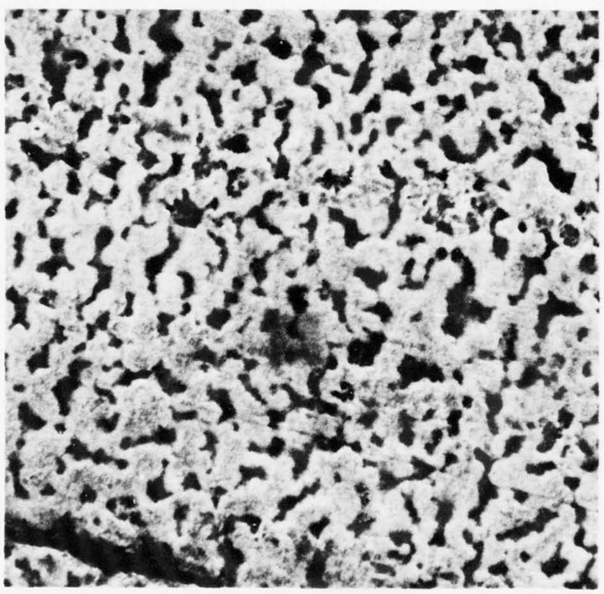
AREA #2



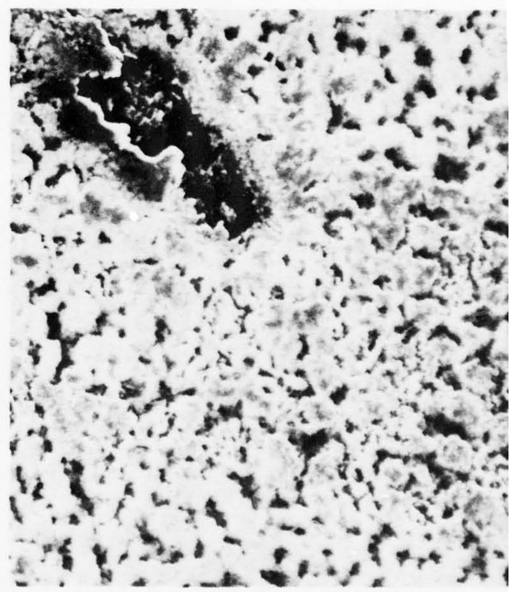
Magnification - 250X



Magnification - 250X



Magnification - 1000X



Magnification - 1000X

INBOARD BEARING L68100

TEST BEARING 420B

HOURS RUN 300

TEST LUBRICANT GREASE D

FIGURE 25 . POST TEST CONDITION OF TEST BEARINGS.

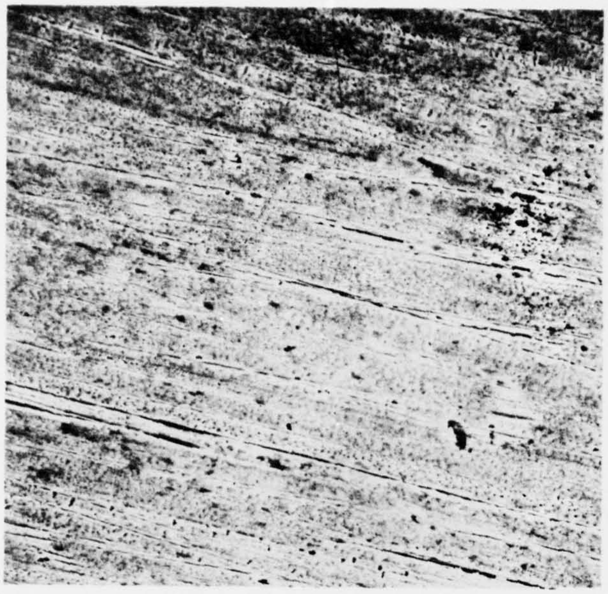
GREASE E

Figures 26 to 29 exemplify the condition of bearings lubricated with Grease E. These bearings are representative of the group which had successfully completed 300 hours of operation. According to the micrographs, many of the grinding lines remain, attesting to a minimally degree of wear. The surfaces of these bearings appear to be microdented extensively as the result of rolling over microdebris. Some of these dents, in fact, have a triangular shape as shown in Figures 27 and 28. Figure 26 shows a localized area of Bearing No. 504A to be partly macrospalled, which was rare in this particular group of bearings.

The condition of this bearing sample is representative of the excellent condition noted previously for the group of bearings in general, and is indicative of good lubrication practice.

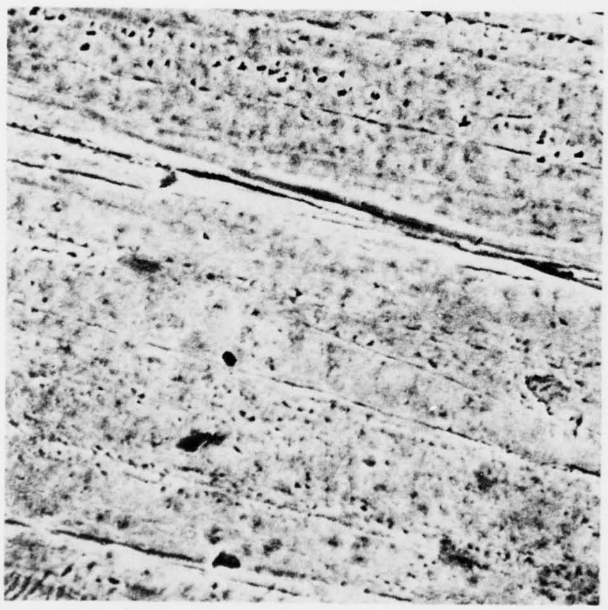
AREA #1

AREA #2

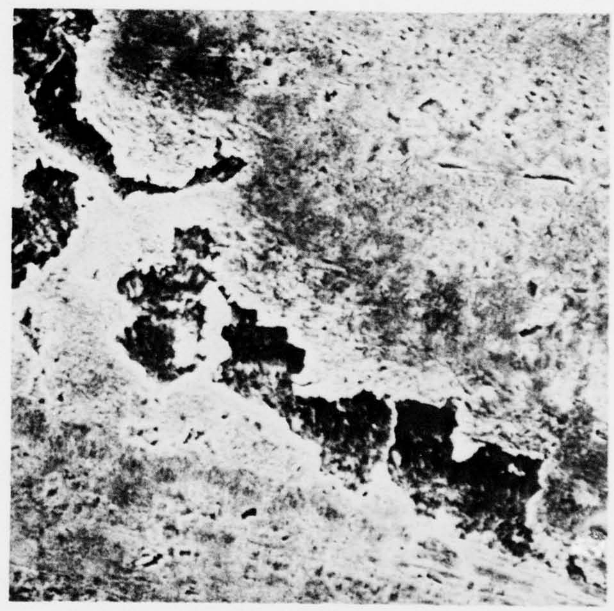


Magnification - 250X

Magnification - 250X



Magnification - 1000X



Magnification - 1000X

OUTBOARD BEARING LM12700

TEST BEARING NO. 504A

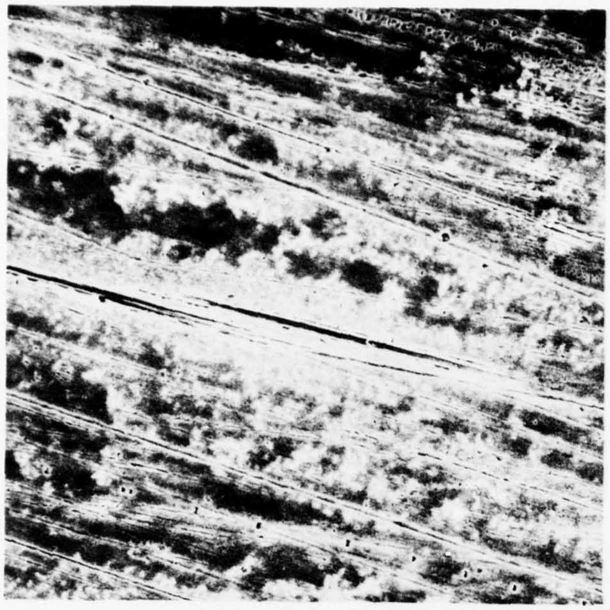
HOURS RUN 300

TEST LUBRICANT GREASE E

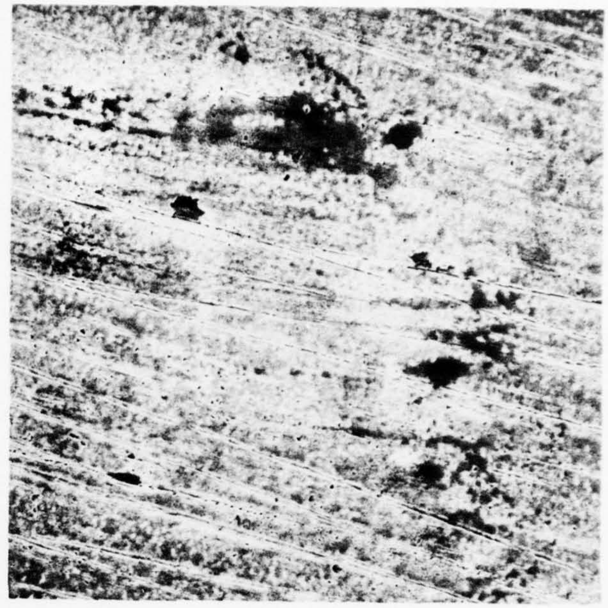
FIGURE 26. POST TEST CONDITION OF TEST BEARINGS.

AREA #1

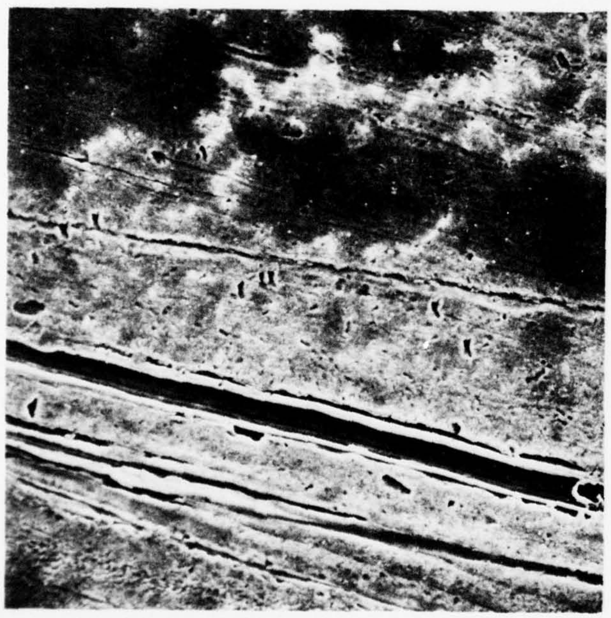
AREA #2



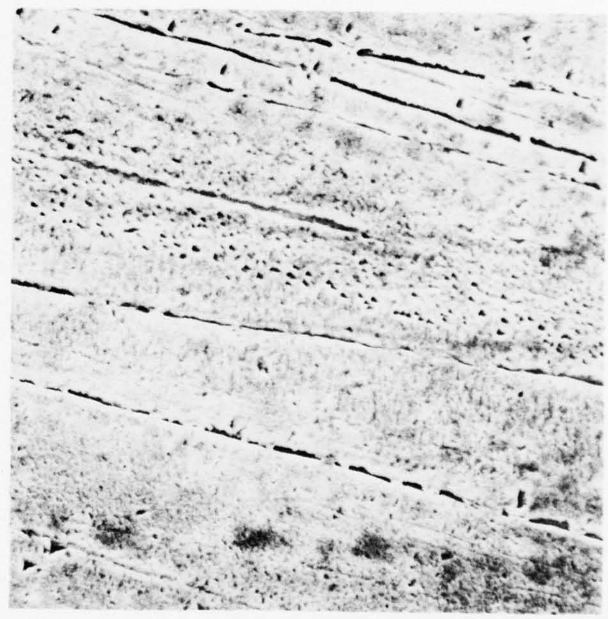
Magnification - 250X



Magnification - 250X



Magnification - 1000X



Magnification - 1000X

OUTBOARD BEARING LM12700

TEST BEARING NO. 505A

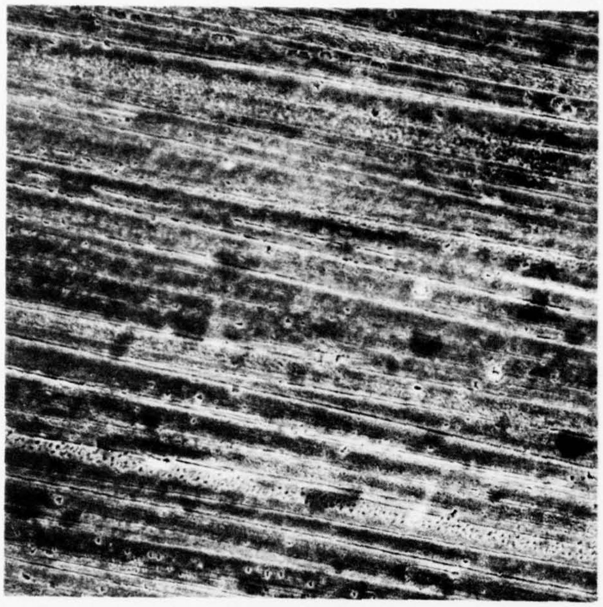
HOURS RUN 301

TEST LUBRICANT GREASE E

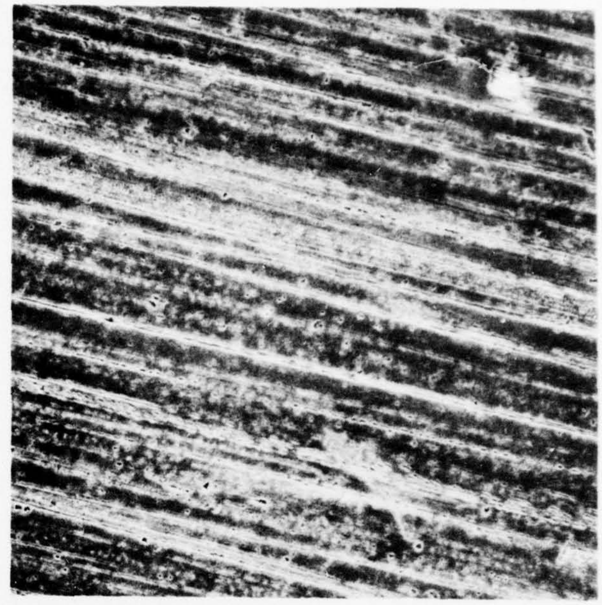
FIGURE 27. POST TEST CONDITION OF TEST BEARINGS.

AREA #1

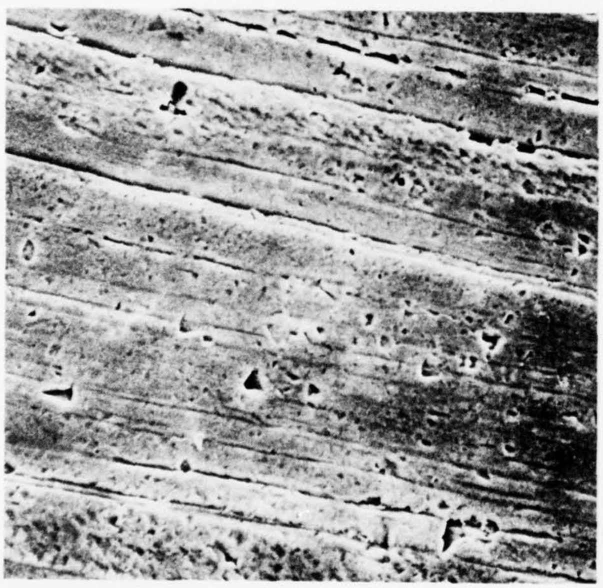
AREA #2



Magnification - 250X



Magnification - 250X



Magnification - 1000X

Magnification - 1000X

INBOARD BEARING L68100

TEST BEARING 504B

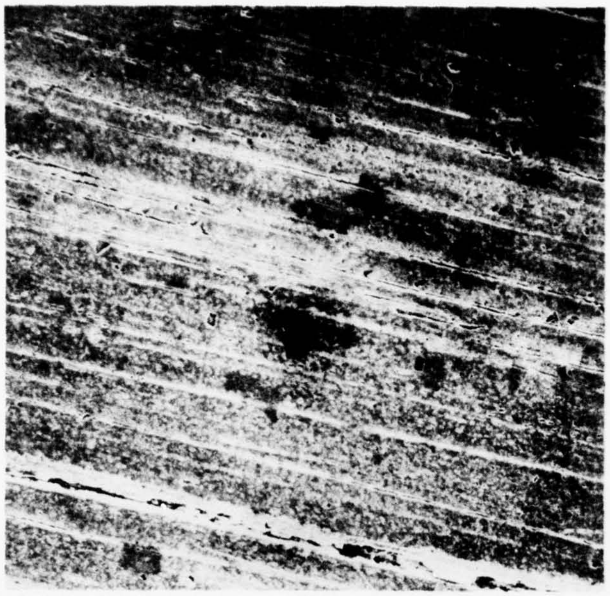
HOURS RUN 300

TEST LUBRICANT GREASE E

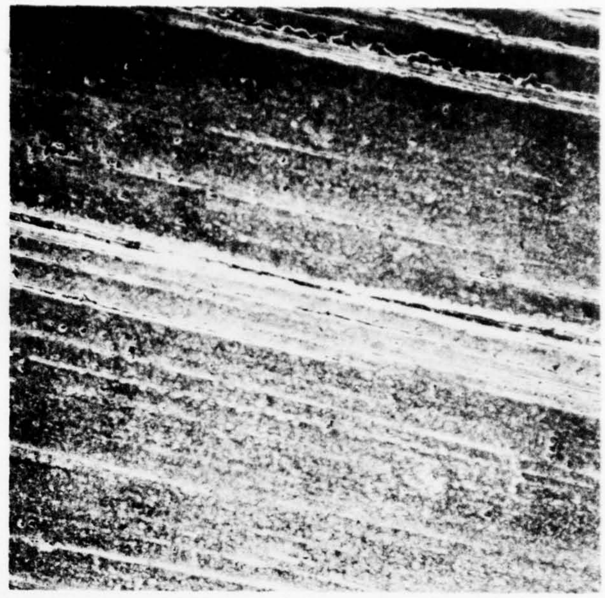
FIGURE 28 . POST TEST CONDITION OF TEST BEARINGS.

AREA #1

AREA #2



Magnification - 250X



Magnification - 250X

Magnification - 1000X

Magnification - 1000X

INBOARD BEARING L68100

TEST BEARING 505B

HOURS RUN 301

TEST LUBRICANT GREASE E

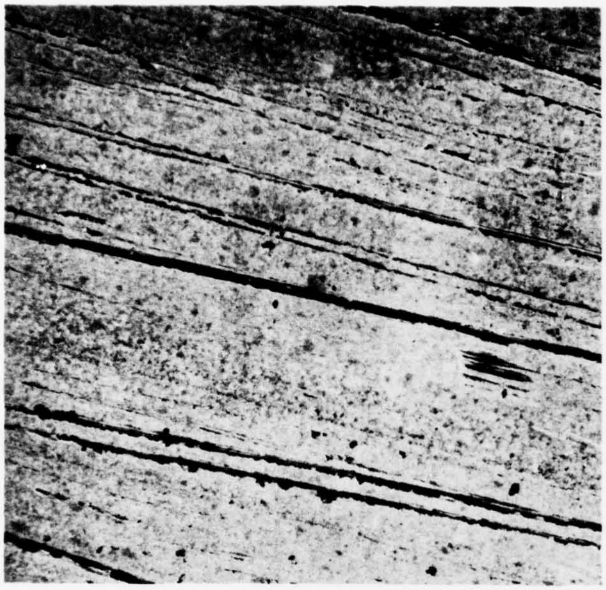
FIGURE 29 . POST TEST CONDITION OF TEST BEARINGS.

GREASE F

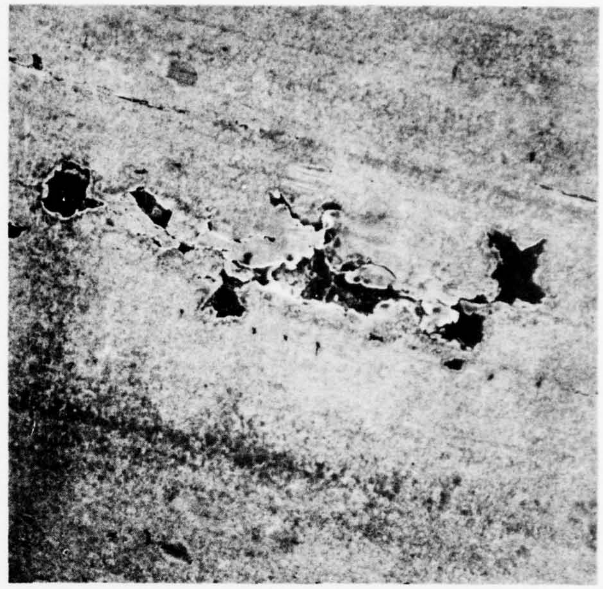
Figures 30 to 33 show the surfaces of cones lubricated with Grease F after 300 hours of operation. The micrographs show that some grinding lines remain indicating only light wear. This is in contrast to Greases A and B which except for oil viscosity are similar in their chemical characteristics. It will be recalled that considerable wear occurred with Greases A and B after only 100 hours of operation.

The surface distress with Grease F ranges from micro to macro (barely visible) spalling, with a moderate degree of glazing. The lubrication characteristics of Grease F appear to be significantly better than Greases A and B, and about equivalent to Grease C.

AREA #1　　　　　　　　　　　　　AREA #2

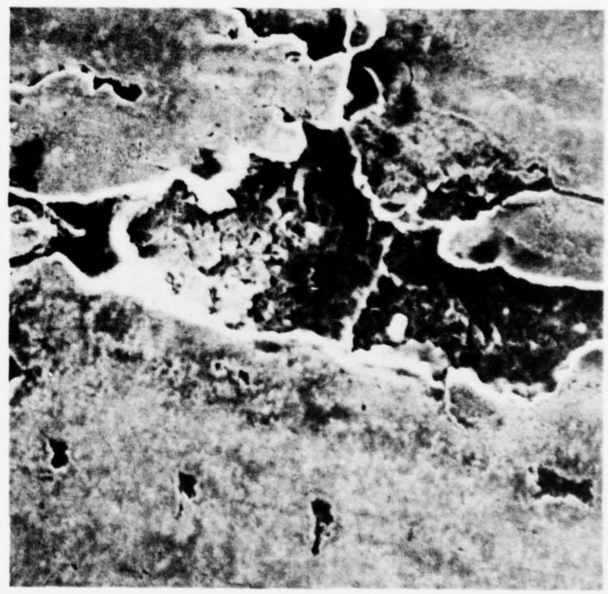


Magnification - 250X



Magnification - 250X

Magnification - 1000X



Magnification - 1000X

OUTBOARD BEARING LM12700

TEST BEARING NO. 603A

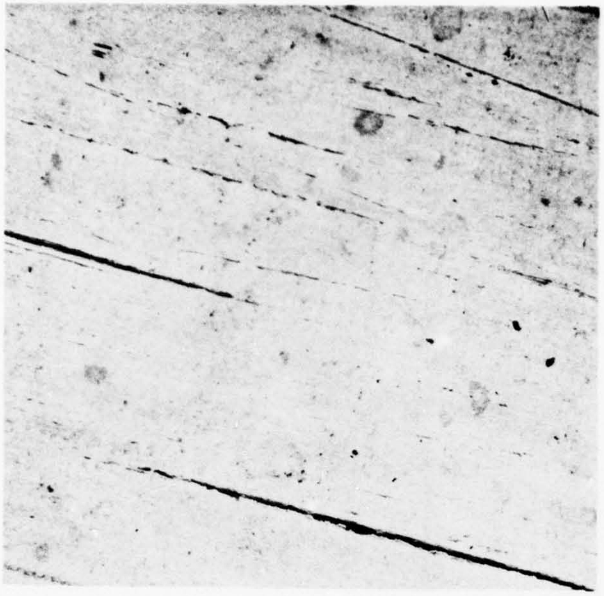
HOURS RUN 312

TEST LUBRICANT GREASE F

FIGURE 30. POST TEST CONDITION OF TEST BEARINGS.

AREA #1

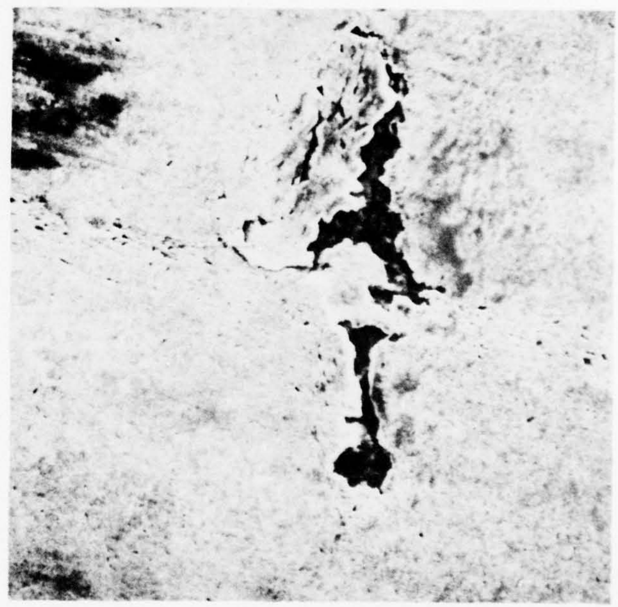
AREA #2



Magnification - 250X

Magnification - 250X

Magnification - 1000X



Magnification - 1000X

OUTBOARD BEARING LM12700

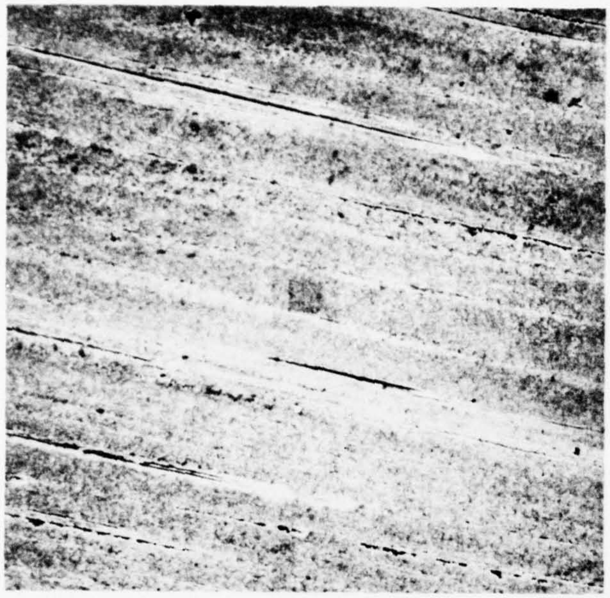
TEST BEARING NO. 604A

HOURS RUN 312

TEST LUBRICANT GREASE F

FIGURE 31 . POST TEST CONDITION OF TEST BEARINGS.

AREA #1

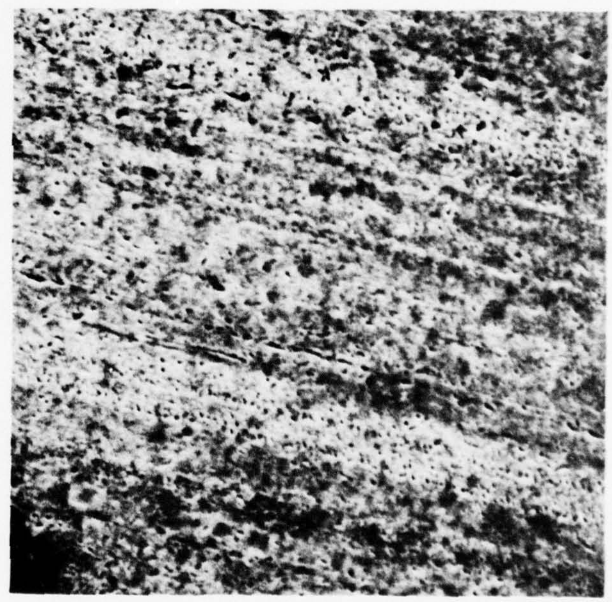


Magnification - 250X

Magnification - 1000X

AREA #2

Magnification - 250X



Magnification - 1000X

INBOARD BEARING L68100

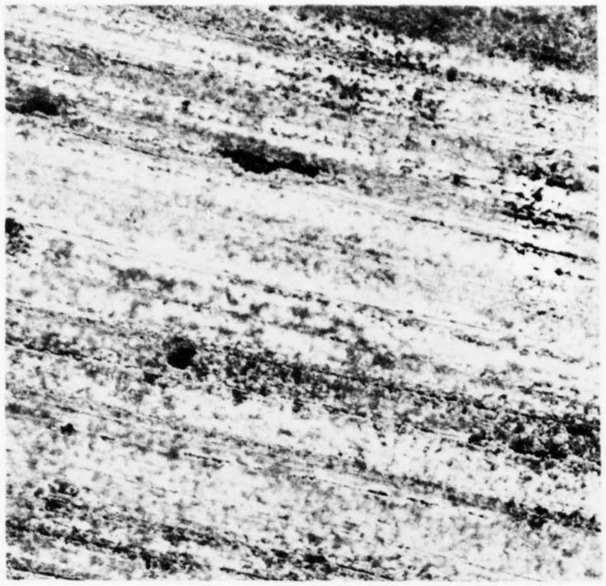
TEST BEARING 603B

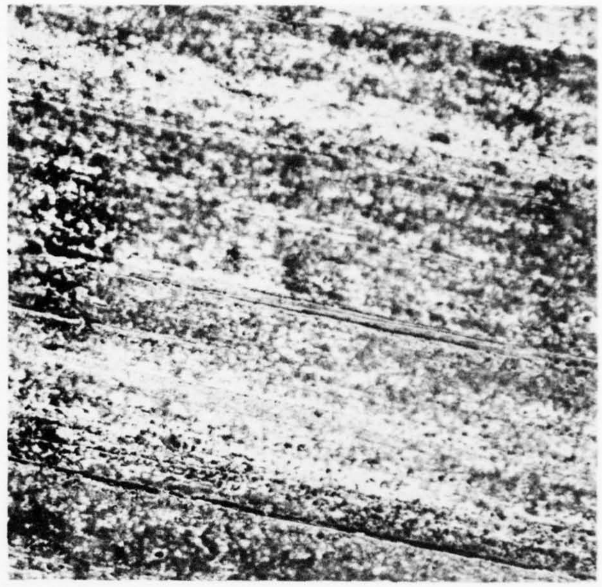
HOURS RUN 312

TEST LUBRICANT GREASE F

FIGURE 32 . POST TEST CONDITION OF TEST BEARINGS.

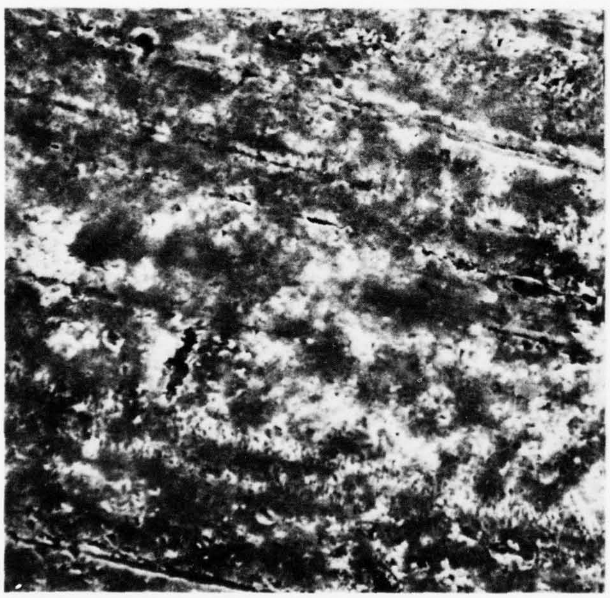
AREA #1 AREA #2





Magnification - 250X

Magnification - 250X



Magnification - 1000X

Magnification - 1000X

INBOARD BEARING L68100

TEST BEARING 604B

HOURS RUN 312

TEST LUBRICANT GREASE F

FIGURE 33 . POST TEST CONDITION OF TEST BEARINGS.

C. PART III - STUDY OF GREASE DETERIORATION

Another aspect of this program is to document the changes that can occur to the chemistry and structure of a grease with use in a front wheel bearing environment. Information, relative to grease performance and deterioration could be useful in the future development of test procedures for the evaluation of candidate greases. Samples of used grease were taken from each of the four bearings of the bearings previously subjected to SEM analysis. By this means an attempt was made to correlate the degree of grease deterioration occurring with that of grease performance. The following describes the procedures employed and the results obtained.

1. Microanalysis of Residual Grease Samples

The extent of alteration to the grease chemistry was based on the analysis of a sample removed from the area of the rolling contact surfaces. The degree of grease oxidation was based upon measurements made on micropenetration, neutralization number, and residual oil content. These values were compared to similar values obtained on a new grease sample and with the values obtained on the other samples of grease.

The following discusses the microanalysis techniques employed to study the changes occurring with use.

Neutralization Number (Acid Number)

In the study of thermal and oxidative degradation of hydrocarbon lubricating oils during their service lives, it is well known that the neutralization number (or acid number) serves as a useful guide to the degree of oxidative deterioration produced during service. In the determination, neutralization number is defined as the weight, in milligrams of potassium hydroxide, required to neutralize the acidic consituents in one gram of sample. The test is performed as potentiometric titration where the meter readings are plotted against the respective volumes of titrating solution and the end points are taken at the inflections of the curve (as per ASTM D664).

Treating a grease as a bi-phase mixture of an oil and a thickening agent, an estimate of lubricant degradation is obtained by separating the oil from the soap with clean petroleum ether, evaporating this down to a few millilitres and determining the acid number of the resultant oil solution.

During the oil and thickener content determinations the oil-phase was leached from the grease sample by solvent extraction and then concentrated by solvent evaporation to a volume of less than one millilitre. To the concentrate was added alcoholic solvent (1 part methanol, 10 parts ethanol and 11 parts water) and the whole titrated potentiometrically with potassium hydroxide using a glass indicating electrode and a calomel reference electrode.

A blank solution, consisting of one millilitre of petroleum ether alcoholic solvent was titrated in the same manner as the sample.

The neutralization number is then calculated from the difference in titre between the sample and the blank in the standard manner. The neutralization number determinations of the used grease samples from the rig tests are tabulated in Table XVI.

Oil Content and Thickener Content

In the oil content measurements approximately 100 mg. of weighed sample grease were placed upon a 13mm, 0.45 micron pore-size milliport filter paper and the oil phase leached out, using petroleum ether as the solvent. The residue was dried at room temperature and weighed. The leaching, drying and weighing procedure was repeated until a constant final weight was achieved. The difference in weight, before and after leaching, was calculated as the oil content of the sample.

The oil contents of the used grease samples from the rig tests are tabulated in Table XVI. The significance of the oil content gradients indicated by those results are discussed later in this report.

Grease Consistency Determination by Penetration

The consistency of a grease sample is usually measured with a standardized apparatus known as a penetrometer, in which the penetration of a steel cone into the grease is measured in tenths of a millimeter. Smaller versions of this apparatus, known as micropenetrometers, are also commercially available, but still require at least 5ml of grease for a consistency determination.

TABLE XVI

CHEMICAL ANALYSIS RESULTS OF TEST GREASES

Brg. No.	Test Hours	% Oil by Weight	Micropen.	Neutralization No.
Grease A				
New Grease		89.2	620	0.20
103a	101	85.3	674	*
104a	129	83.1	662	1.66
104b	129	87.0	647	*
114b	86	**	***	1.45
Grease B				
New Grease		91.7	628	0.11
203a	106	78.7	741	1.52
204a	131	79.9	708	1.90
206b	119	83.3	***	0.81
220b	109	80.9	***	*
Grease C				
New Grease		90.9	612	0.16
301a	102	89.7	625	*
305b	167	88.2	640	*
309a	96	88.3	603	*
309b	96	88.2	614	1.68

* No clearly defined endpoint

** Insufficient sample for determination

*** Insufficient sample for determination

AD-A068 829 SKF INDUSTRIES INC KING OF PRUSSIA PA TECHNOLOGY SERV--ETC F/G 11/8
RESEARCH REPORT ON PERFORMANCE OF AUTOMOTIVE WHEEL BEARING GREA--ETC(U)
OCT 78 N J NINOS, F R MORRISON, J I MCCOOL DAAK70-77-C-0034

UNCLASSIFIED SKF-AL78T022 NL

2 OF 2

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MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

TABLE XVI
(CONTINUED)

Brg. No.	Test Hours	% Oil By Weight	Micropen.	Neutralization No.
Grease D				
New Grease		95.3	660	0.14
406a	306	82.3	620	0.41
406b	306	89.4	640	0.34
420a	300	81.0	**	0.99
420b	300	82.5	635	0.91
Grease E				
New Grease		87.4	605	0.33
505a	301	81.6	665	*
505b	301	83.1	700	0.61
504a	300	77.0	610	0.75
504b	300	79.2	675	0.54
Grease F				
New Grease		89.4	630	0.06
603a	312	53.2	**	*
603b	312	74.0	520	0.60
604a	312	57.9	490	1.78
604b	312	67.9	**	1.42

* No clearly defined endpoint

** Insufficient sample for determination

In order to achieve a determination from a grease sample of approximately 10mm^3 (10 mg) a micropenetrometer apparatus was modified (8) by replacing the grease holder with one of lesser volume having a test chamber 0.0525" in diameter, and by replacing the standard cone with a tapered needle the shape of which is shown in Figure 34. A dial gauge measured the depth of needle penetration into the grease in hundredths of a millimeter. The shaft of the dial gauge was drilled out to reduce the driving weight on the needle to a total penetration force of 9.50 gr. The arithmetic mean of at least five individual micropenetration determinations from each grease sample are shown in Table XVI. These results are illustrative of the changes in penetration values that occur with grease use in a bearing.

In the following discussion, it should be noted that the used grease samples of A, B and C were 100 hour samples while used grease sample of D, E, F were 300 hour samples.

Oil Content

The oil content values for the used grease samples are consistantly lower than the new grease values. Generally, the degree of oil depletion is more marked for the longer run greases than for those run 100 hours.

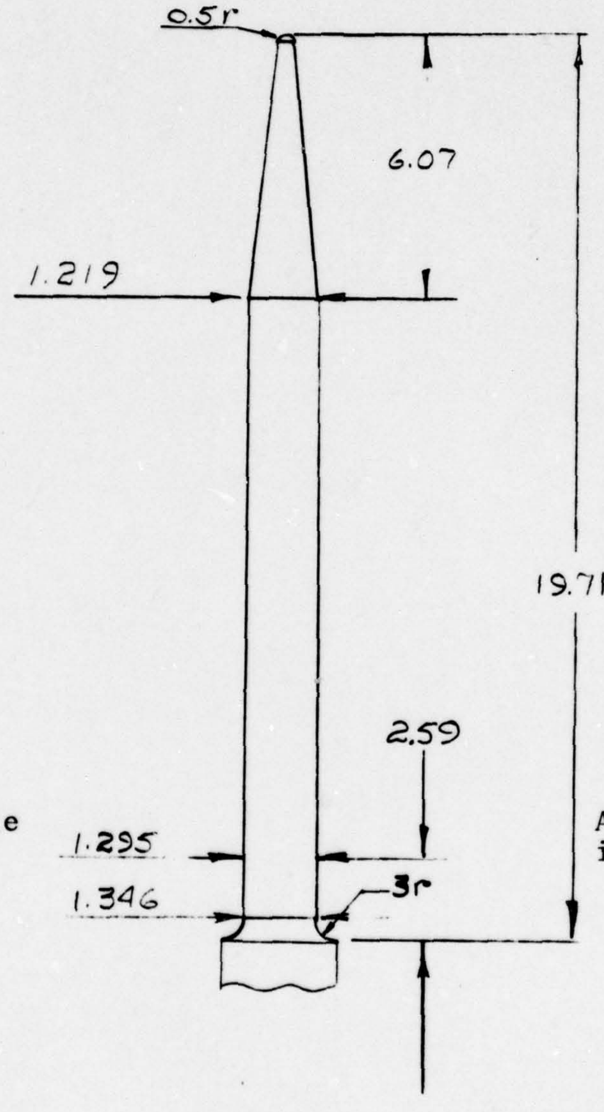
The depletion ranking is as follows:

$$F > D, E, B > A, C$$

where the approximate percentage losses were:

30% - 40%, 12% - 15%, 3% - 5%

Grease F shows pronounced oil loss. However, it is pointed out that this was after running three times as long as Greases A, B and C. This is also true of greases D and E, which showed a greater percentage oil loss than Greases A and C.



Weight of Needle
0.75 gr.

All Dimensions
in Millimeters

FIGURE 34

MICROPENETROMETER TEST NEEDLE

Neutralization Number

Oxidation of the oil phase component in a grease leads to generation of organic acids. The neutralization number is a measure of the acidity, hence the degree of oxidation. Readings of less than 0.8 Mg KOH may be considered insignificant in this work. Levels above 1.25 Mg KOH indicate definite lubricant acidity. Examination of the data reveals the following ranking of greases in terms of the average acid level in the used samples:

$$B, A, C > F > D, E.$$

The differences in the running time between A, B, C and D, E, F further emphasises the differences in oxidation resistance:

$$B, A, C \ll F \ll D, E.$$

Micropenetration Results

These data indicate a general softening of the grease after running. In cases of substantial oil depletion, this softening, in spite of increased thickener concentration, must be due to a decrease in thickener stabilizing capacity. In the case of grease F, the relatively greater oil depletion of the used samples due to the longer operation resulted in an increased stiffness of the grease despite the above softening effect. However, this observation does not appear to detract from the good lubrication characteristics observed in comparison to Greases A and B.

2. RESULTS OF SEM ANALYSIS OF GREASE STRUCTURE

Subsequent to the micro grease analysis, the grease was to be subjected to SEM analysis to define alterations of the thickener structure. However, experimentation with samples of unworked grease has illustrated that it is extremely difficult to obtain scanning electron micrographs which are repeatable enough to allow definition of alterations in the structure.

This effort was initiated using a grease sample preparation technique developed at Shell and described in the literature. [9] The purpose of the technique is to remove the oil from the grease without altering the residual thickener either chemically or mechanically. The residue can then be gold coated for examination in the SEM. Early attempts quickly established that this method did not provide reproducible samples so variations in the preparation technique were evaluated.

Parameters studied to achieve reproducibility were:

(1) The type of solvent used and

(2) The time of de-oiling

Scanning electron micrographs of the soap structures were obtained by de-oiling the commercial grease using N-hexane, benzene and iso-octane. The structure produced by de-oiling with N-hexane contained the expected porosity in which oil is retained in a grease, but the others had not. During this study,it was also found that soap fibers should not be held under the electron beam for very long, as it causes the soap to melt. The high voltage used was 20KV and the beam current was 2.2 mA. It was decided from this finding that future studies should use a high voltage of 10KV with a beam current of about 1.8 mA for adequate contrast in the photographs. In general, as the accelerating voltage is reduced it becomes necessary to reduce the beam current to maintain tolerable contrast on the photographs.

A similar comparison of soap structures were obtained on samples of Grease A using benzene and N-hexane for de-oiling. De-oiling by N-hexame is seen to be superior. An accelerating voltage of 10KV was used in the scanning electron microscope.

The time of de-oiling also seems to have an effect on the quality of structure produced after de-oiling. The overall structure obtained after a 2 hour de-oiling was observed to be more open than one obtained after 17 hours of de-oiling. This may be due to a collapse of the de-oiled structure by prolonged action of capillary forces on the soap fibers. It is therefore important to minimize the de-oiling time as much as possible. An area on the 2 hour de-oiled sample was held under the electron beam for a few minutes for observation. During this time, it was found that the structure continued to open as if something was being removed from it. This indicates that the procedure used for de-oiling may not have completely removed all of the contained oil. Some of the residual oil may have been removed by the action of the electron beam and vacuum during scanning electron microscopy. This suggests that application of modest amounts of heat coupled with vacuum may be a plausible way to de-oil grease samples for study of the soap structure. Use of solvent vapors may be another way by which properly de-oiled grease samples can be produced.

The above study indicates the need to conduct a rather detailed investigation of sample preparation techniques in order to improve the reproducibility of the samples presented for SEM evaluation. Due to the inconsistencies contained in the results, it was decided to suspend activity in this area.

III. DISCUSSION OF RESULTS

A. Endurance Life as Affected by Grease Type

A statistical analysis of the bearing life data for each of the greases evaluated, using the maximum likelihood technique has yielded the following estimates of the L_{10} life. The greases are listed in the order of increasing life for the groups of bearing sets employed as test specimens.

Grease	Median L_{10} Life of Bearing Sets in Million Revs
A	1.68
B	1.42
F	4.69
C	5.81
D	6.18
E	15.97

The theoretical L_{10} life for the combined bearing system i.e., bearing set is 11.3×10^6 revolutions. A comparison of the above results, with the theoretical value, shows that the high test loads and artificially elevated ambient temperature severely stressed the lubricants and except for Grease E produced a life reduction effect.

Laboratory studies have shown that fatigue life and wear of a rolling contact bearing is critically dependant upon the minimum thickness of the hydrodynamic oil film in the contact area, as compared to the surface roughness of the rolling parts. Surface distress occurs when the film is too thin and therefore does not adequately separate the asperities at the rolling contacts. SKF has applied this knowledge in the development of the elastrohydrodynamic lubricant parameter Λ (lambda) to rate the effectiveness of lubrication in ball and roller bearing applications (10). Λ is described as follows:

$$\Lambda = H\,[\mu_o \alpha N]^{0.73}\, P_o^{-0.09}$$

Λ is the ratio of film thickness surface roughness

where: H pertains to bearing geometry

μ_o is the dynamic viscosity in lb-sec/in^2 at the operating temperature

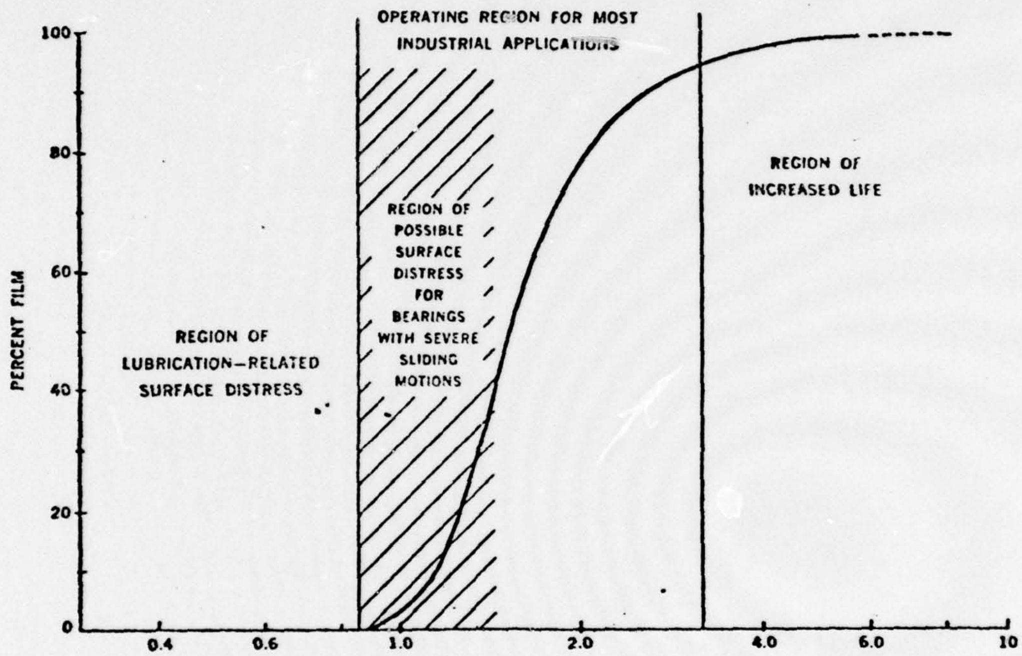
α is the pressure coefficient of viscosity in I/PSI

N is the speed of the bearing

and P_o is the equivalent load on the bearing

A qualitative picture of the effect of the lubricant film thickness on bearing endurance is shown below.

PERCENT FILM VS Λ



In this illustration, percent film refers to the time percentage in an operating bearing during which metal-to-metal contact is prevented by the presence of the lubricant film. As shown the value of Λ falls between 0.8 and 4 for most applications. It is very much dependant upon the viscosity of the lubricant at the operating temperature of the bearing.

While this technique was developed for oil lubrication, past studies have shown that some correlations exist for grease lubricated bearings by considering the viscosity of the base oil. Therefore, Lambda values (11) have been calculated for the six greases on the basis of the oil viscosity at a bearing operating temperature of 394°K (250°F). The values for the two bearing sizes are given in Table XVII.

TABLE XVII

Comparison of Endurance, Film Thickness Parameter and 4 Ball Extreme Pressure Values

Grease	Median L_{10} Mil. Revs.	Oil Viscosity SSU@121°C	Oil Viscosity $\mu_0 \alpha^{0.78}$ $\times 10^{-8}$	Elastohydrodynamic Parameter LAMBDA LM12700	Elastohydrodynamic Parameter LAMBDA L68100	4 Ball Extreme Pressure Load Wear Index
A	1.681	33.3	1.8	0.076	0.098	35.6
B	1.422	33.3	1.8	0.076	0.098	32.1
C	5.805	54	5.2	0.221	0.283	40.0
D	6.176	39	2.2	0.093	0.120	40.5
E	15.97	83	9.0	0.382	0.490	92.0
F	4.694	37.5	3.2	0.136	0.174	37.9

These are based upon the following parameters:

Bearing	H	N (rpm)	P_o (Kn)
LM12700	6.4×10^4	800	7.397
L68100	8.59×10^4	800	12.352

H = Value pertaining to a given bearing geometry and dimensions, (11) Examination of the Lambda values in Table XVII points out that the bearings are operating in a region of marginal lubrication which is prone to surface distress. With Lambda values of 0.1 to 0.5 the likelihood of metal-to-metal contact at the rolling contacts is probable. Except for Grease E, which exceeded the theoretical L_{10} life, this factor explains the reduced life obtained for the other five greases and the poor condition of the rolling contacts observed by means of SEM micrographs. The SEM micrographs verify the occurrance of surface distress predicted by the low Lambda values.

Despite the extremely thin oil films available on the basis of the viscosity of the oil employed at the operating temperature run, a plot of the Lambda values against the median L_{10} life, Figure 35 indicates that there is a viable relationship between these two factors. Accordingly, those greases having a relatively higher viscosity, hence Lambda value, also have a proportionally higher life.

Greases A and B conform to MIL-G-10924C. Grease F has a higher oil viscosity and will meet a modified version designated as MIL-G-10924 D proposed. All three greases have a calcium base and the oil is from a napthenic stock.

Grease F provided a higher life than A or B, probably as the result of having a 50% thicker oil film, which also accounts for its higher EP value according to the Four Ball Extreme Pressure Index Value noted in Table XVII.

Using the same hypothesis, the superiority of Grease E, a lithium product with a paraffinic oil stock, is explained by its higher oil viscosity and EP characteristics. The bearings lubricated with Grease E were the highest lived (L_{10} = 15.97 mil. revs.) which correlates with the highest Lambda and EP values of the greases evaluated. In addition, Grease E had the lowest wear rate indications as observed from the SEM micrographs. This grease is intended for high temperature use, i.e., 623^{o}K (350^{o}F).

Grease C, another lithium based product, but having a lower viscosity paraffinic oil had a significantly lower life than Grease E, but much better than Greases A and B. Its EP characteristics also had the same relationship, i.e., lower than E, but higher than A and B.

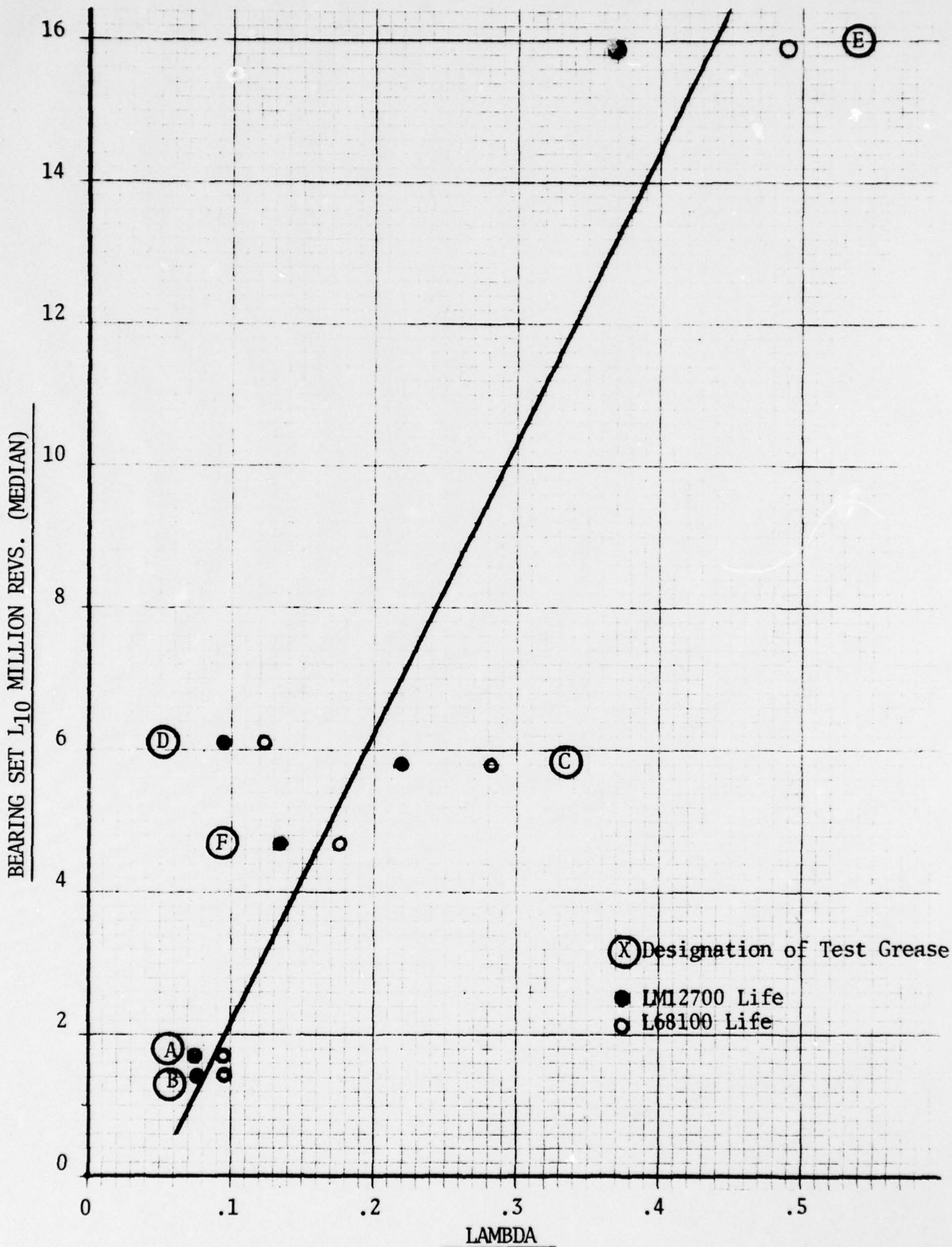


FIGURE 35. Bearing Life as a Function of the Elasto-hydrodynamic Film Parameter

Grease D a Bentonite clay thickened product contains a synthetic hydrocarbon oil having a viscosity equivalent to Grease F. The life of the bearings lubricated with Grease D is equal to that of C and marginally better than F. The EP characteristics of all three greases are the same, in spite of the fact that C contains a more viscous oil than either D or F. The peculiar pattern of surface damage noted on the SEM micrographs with Grease D may have been caused by the fine particles in the clay thickener being pressed into the surfaces by the extremely high pressures occurring at the rolling contacts. This grease is a general purpose aircraft grease and capable of operation from 208^{o}K to 623^{o}K (-65^{o}F to 350^{o}F).

Generally, the smaller LM12710/LM12749 bearings had fewer and smaller microspalls in comparison to the larger, companion, L68110/L68149 bearings. Undoubtedly, the greater damage was produced by the higher force the larger bearing is under during the application of the thrust load.

B. Correlation of Grease Performance with Grease Chemistry

There appears to be a basic correlation between grease performance and the extent of deterioration with most greases. Table XVIII presents a comparison of the averages of the results obtained for percent oil remaining, micropenetration, and neutralization number, for the used samples of greases removed from the bearings after a finite time of operation.

Although a direct comparison for greases A and B, and F are not possible due to the differences in operating time shown, the neutralization number of F is less than A and B even though F ran three times longer which indicates that F's resistance to oxidation is better.

Grease C faired better than A and B probably due to the fact that its base oil had a heavier viscosity. However, its shear strength appears to be better since it softened only slightly with work and it had less oil loss. The rate of deterioration for the three greases appears to be equal.

Least deterioration was experienced with Greases E and D which also gave the best performance in that order. The neutralization numbers were less than half of the other four greases. Grease E tended to soften while D hardened with use, and E had less oil loss.

TABLE XVIII

COMPARISON OF GREASE DETERIORATION

AVERAGE VALUES USED GREASE

Grease	Test Hours	% Oil By Weight	Micropen.	Neutralization No.
A	111	85.1 (89.2)	661 (620)	1.56 (0.20)
B	116	80.7 (91.7)	725 (628)	1.41 (0.11)
C	100	88.6 (90.9)	621 (612)	1.68 (0.16)
D	303	83.8 (95.3	632 (660)	0.66 (0.14)
E	300	80.2 (87.4)	663 (605)	0.63 (0.33)
F	312	63.3 (89.4)	505 (630)	1.27 (0.06)

(   ) Values of New Grease

C. SUMMATION OF DISCUSSION

Although the majority of the bearings, which had not failed due to gross spalling of the rolling contacts or overheating, appeared to be serviceable, the surface morphology of these bearings had been affected to various degrees. On the low lived bearings, the degree of surface damage was excessive. The microspalls ultimately nucleated a larger spall which resulted in the bearings final destruction. The higher lived bearings exhibited less distress, but the nature of the surface condition noted even after 300 hours operation which represents 14.4 million revolutions is still believed to be detrimental to the continued service life of a bearing.

The bearings lubricated with Grease E had the least observable damage and wear. Visually these bearings appeared to be in the as new condition. But even these bearings displayed mild distress normally associated with marginal lubrication, when studied in more detail using the SEM.

Under normal operation conditions, general commercial automotive practice dictates that wheel bearings should be regreased every 64,000 kilometers. This regreasing interval is then reduced if the vehicle is operated under adverse conditions, i.e., off the road. Military vehicle practice conforms to these limitiations; road use vehicles are regreased following commercial recommendations, while field vehicles have regrease intervals ranging from 1,600 to 19,200 kilometers.

The rigorous operational conditions imposed by this test have substantially reduced the potential life of the bearings and make it impossible to comment on the acceptability of existing service regreasing practices. Moreover, it has been shown that the performance of a bearing is highly dependent upon the type of grease employed. However, relative comparisons can be made between the samples tested. To facilitate the application of the data to the every day application, the L_{10} life data in millions of revolutions of each grease (see page 89) have been expressed in terms of kilometers of operation as shown below:

Grease	Median L_{10} Life Kilometers of Operation	Ratio of Average Current Grease To Sample
B	2,930	
A	3,470	1.0
F	9,680	3.0
C	12,000	3.7
D	12,750	4.0
E	32,960	10.3

From these results, it is indicated that bearing service life, and therefore field regreasing intervals, can be extended with the use of a proper lubricant. However, the extrapolation of these test results obtained at an artifically high operating temperature for the actual prediction of extended service life is premature at this time without a correlation of field service data, and more extensive laboratory data. Nonetheless, it is considered that reasonable comparisons of grease performance can be made on the basis of the test results and that these rankings would be valid in the field situation. However, the magnitude of the variations seen between the groups would most probably be different.

With this in mind, it can be seen that the utilization of the commercial product should provide enhanced operating capabilities over those currently being obtained with the military specification greases. It is also indicated by this limited data that a comparable extension in performance and therefore the acceptable regreasing interval could be achieved with Grease F, manufactured to the new proposed grease specification.

While the aircraft specification Grease D and general purpose (high temperature) Grease E seem to offer even better capabilities than the wheel bearing greases evaluated, their use may be precluded by their higher cost, and the probably inadequacy of Grease E at low operating temperatures.

IV CONCLUSIONS

The relative performance characteristics of an automotive type front wheel bearing grease can be assessed in a laboratory environment according to the procedures outlined in this report. On this basis, the following conclusions have been drawn.

1. The lubrication characteristics of the commercial wheel bearing product, Grease C, are better than those of either of the two current military specification wheel bearing Greases A and B.

2. The performance of Grease F, made to the proposed wheel bearing grease specification, is equivalent to that of the commercial Grease C, and better than that of the two current military specification Greases A and B.

3. The General Purpose (high temperature) Grease E, and the Military Aircraft Grease D were rated as having the best overall performance. However, their use in automotive wheel bearings may be precluded by their relatively high cost and possible inapplicability to the total range of operating conditions of the application.

4. An apparent correlation exists between bearing endurance achieved with the six greases, and the values of the elastohydrodynamic parameter (lambda), the four ball extreme pressure value index, the extent of lubricant deterioration, and the degree of damage and/or wear occurring on the rolling contact surfaces of a bearing.

   The better performing greases had higher oil viscosities and consequently higher values of lambda, extreme pressure index, and less deterioration.

RECOMMENDATIONS

This program has produced a laboratory test sequence which can be utilized to rank the performance of automotive wheel bearing greases, and provides a preliminary data base of performance characteristics which can serve as a basis of comparison for future candidate lubricants.

While these data are adequate for the formulation of preliminary conclusions on wheel bearing grease performance, the need to expand the data base is required in order to extend the comparative range of the data, and to establish the precision of the test method.

Specifically it is recommended that two additional laboratory tests be performed; the first with another commercial grease, and the second with the same sample of one of the current military greases without the addition of heat. The commercial grease tested in the program is utilized by a major automotive manufacture as a factory fill product, and is, therefore, a grease of proven performance. The factory fill product of a competitive automotive manufacturer, however, has a significantly different composition which may yield different performance characteristics under this test method. The testing of this second commercial grease is necessary to complete the comparison of military and commercial greases, and to facilitate the utilization of commercially experience in the generation of lubrication guidelines for military vehicles.

The second laboratory test to be run with the current military grease, but without heat, is recommended to establish the magnitude of the effects of heat on lubricant performance. It is expected that the results of this test would be more likely to approximate those occurring in field service and therefore, facilitate the extrapolation of the laboratory data to the field conditions.

The results of the test sequences completed to date indicate that the grease compounded to a proposed specification has performance characteristics which are superior to those of current military wheel bearing specification greases. It must be remembered, however, that the grease sample tested had been formulated in a small batch under laboratory conditions. This being the case, it is not known whether these good performance characteristics would be repeated with another laboratory formulated grease sample or with a grease made by production methods.

It is therefore recommended that a new laboratory formulated grease sample be evaluated and, once repeatability has been established, an additional test be run using a grease sample prepared by commercial production techniques.

The total potential of this laboratory method of evaluating wheel bearing greases will only be realized after a reasonable correlation with field experience is established. It is therefore recommended that a field test be conducted utilizing military vehicles in controlled service, and with controlled grease samples of the type evaluated in the laboratory. Periodic examinations of the condition of the grease and bearing surfaces at known distances, employing the techniques contained in the established laboratory test sequence, will provide the necessary data. These data can then be used to establish grease/bearing performance as a function of vehicular use for known operating conditions. This relationship can in turn be utilized to extrapolate the results of laboratory tests to the same set of field operating conditions.

APPENDIX I

Method of Calculation to Determine the L_{10} Life of the Test Bearing System

The L_{10} life of the two bearing system employed as calculated here in is based upon formulas and methodology concepts currently in use by the bearing industry.

The test conditions employed were:

1. Test Bearing Specimens

   Outboard - LM12749/LM12710 = Brg. 1
   Inboard - L68149/L68110 = Brg. 2

2. Applied Radial Load - 8.34 Kn (1875 lbs.)
   Applied at a distance of 45.847 mm (1.805 in.) from the outboard bearing pressure center (See Figure 36)

3. Thrust Load - 2.49 Kn (560 lbs.)
   Applied 30% of the time at a distance of 34.163 cm (13.45 in.) from the horizontal axis of the bearing centerline.

4. Speed - 800 rpm

5. Distance between the outboard bearing and inboard bearing pressure centers is 70.536 mm (2.777 in.).

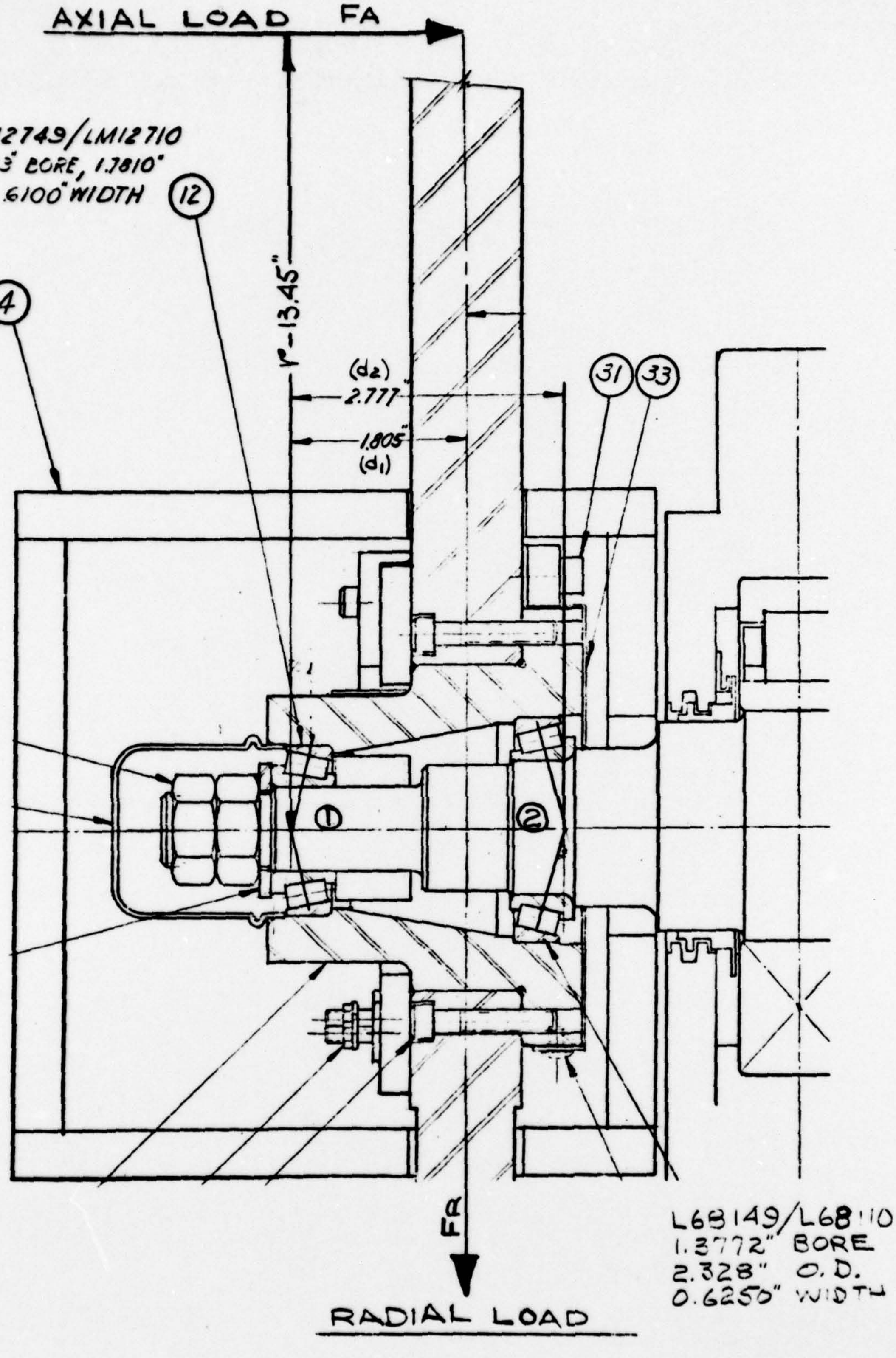


Figure 36
Location of Applied Forces

LIST OF SYMBOLS AND TERMS

L_{10} = ls the life 90% of the bearings are expected to exceed

P = Equivalent Load

Fr = Radial Force on Bearing

FR = Applied Radial Load

Fa = Applied Force on Bearing

FA = Applied Axial Load

Y = Thrust Factor From Bearing Catalog

d_1 = Distance From an Outboard Bearing Pressure Center to FR

d_2 = Distance Between Outboard and Inboard Bearing Pressure Centers

r = Distance Between Horizontal Bearing Axis and F_A

T_r = Induced Thrust Force Due to Applied Radial Force

C = Industrial Radial Load Rating (Catalog)

Z = Constant 3.86. Whenusing the published Industrial Load Rating, it is necessary to convert from a life basis of 90×10^6 revs to a life basis of 1×10^6 revs by multiplying the industrial rating by 3.86.

N = Bearing Speed rpm

The equivalent load P on which the life formula

$$L_{10} = \left(\frac{C}{P}\right)^{10/3}$$

is based upon was calculated from the accumulated forces on the system occurring from the application of (a) radial load only and (b) the combined radial and axial loads as the result of the moment caused by the application of a force at the tire radius.

The determination of P for the first condition for straight radial load is based upon the loads applied to each individual bearing determined as follows:

First Condition - Straight Radial Load Only

$\Sigma M_1 = 0$ (See Figures 34)

$$FR_2 = \frac{d_1(FR)}{d_2} = \frac{1.805(1875)}{2.777} = 1218 \text{ lbs.}$$

Thrust force induced by Fr_2 force.

$$T_2 = \frac{0.47\ Fr_2}{Y_1} = \frac{0.47(1218)}{1.4} = 409 \text{ lbs.}$$

$$Fr_1 = \frac{d_2-d_1}{d_2}(FR) = \frac{2.777-1.805}{2.777}(1875) = 656 \text{ lbs.}$$

$$T_1 = \frac{0.47\ Fr}{Y_2} = \frac{0.47(656)}{1.91} = 161 \text{ lbs.}$$

Then:

$$P_2 = 1218 \text{ lbs.}$$

$$P_1 = 0.4\ Fr_1 + Y\ (T_2)$$
$$= 0.4\ (656) + 1.91\ (409) = 1044 \text{ lbs.}$$

Second Condition - Sum of Radial, Axial and Moment Loads

$\Sigma M_1 = 0$

$Fr_2 = \frac{d_1(FR + r(FA)}{d_2} = \frac{1.805(1875) + 13.45(560)}{2.777} = 3931$ lbs.

$T_2 = \frac{0.47(3931)}{1.4} = 1319$ lbs.

$Fr_1 = Fr_2 - FR = 3931-1875 = 2056$ lbs.

$T_1 = \frac{0.47(2056)}{1.91} = 506$ lbs.

The applied force FA = 560 lbs.

Then:

$P_2 = 3931$ lbs.

$P_1 = .4\ (2056) + 1.91\ (1319-560) = 2273$ lbs.

Since the loads on the bearings are applied cyclically i.e., the axial load is applied only 30% of the time and the radial force is constant, the equivalent load P_Q for each of the bearings must be calculated according to the cubic mean value established for the loads applied at each time interval.

In this case:

$$P_Q = \left[0.7\ (P_{1st\ condition})^{10/3} + 0.3\ (P_{2nd\ condition})^{10/3}\right]^{0.3}$$

Accordingly:

$$P_{Q_2} = \left[0.7(1218)^{10/3} + 0.3(3931)^{10/3}\right]^{0.3} = 2777 \text{ lbs.}$$

$$P_{Q_1} = \left[0.7(1044)^{10/3} + 0.3(2273)^{10/3}\right]^{0.3} = 1663 \text{ lbs.}$$

And:

$$L_{10} = \left[\frac{C(Z)}{P_Q}\right]^{10/3} = \left[\frac{C(3.86)}{P_Q}\right]^{10/3} \frac{10^6}{60(N)} = \text{Hours}$$

$$L_{10_2} = \left[\frac{1610(3.86)}{2777}\right]^{10/3} \frac{10^6}{60(800)} = 304 \text{ Hours}$$

$$L_{10_1} = \left[\frac{1280(3.86)}{1663}\right]^{10/3} \frac{10^6}{60(800)} = 784 \text{ Hours}$$

The life of the system i.e., the two bearings is

$$\frac{1}{L^e} = \frac{1}{(L_1{}^e)} + \frac{1}{(L_2{}^e)}$$

where $e = 1.125$

Therefore:

$$\frac{1}{L^e} = \frac{1}{(304)^{1.125}} + \frac{1}{(784)^{1.125}} = \frac{1}{622} + \frac{1}{1804}$$

$$\frac{1}{L^e} = 0.0016 + 0.00055 = 0.00216$$

$$L^{1.125} = 463$$

$L = 234$ Hours or 11.3×10^6 revs.

LIST OF REFERENCES

1. McCool, J. I., "Evaluating Weibull Endurance Data by the Method of Maximum Likelihood", ASLE Trans., No. 13, 189-202 (1970).

2. McCool, J. I., "Inference on Weibull Percentiles and Shape Parameter from Maximum Likelihood Estimates", IEEE Trans. on Reliability, No. R-19, 177-59 (1970).

3. McCool, J. I., "Censored Sample Size Selection for Life Tests", Proceedings 1973 Annual Reliability and Maintainability Symposium, IEEE Cat. No. 73CH0714-64 (1973).

4. McCool, J. I., "Analysis of Variance for Weibull Populations", in the Theory and Applications of Reliability, edited by C. Tsokos and I. Shimi, Academic Press, (1977).

5. McCool, J. I., "Competing Risk and Multiple Comparison Analysis for Bearing Fatigue Tests", ASLE Trans. Vol. 21, No. 4, (1978) pp. 271-284.

6. McCool, J. I., "Analysis of Single Classification Experiments Based on Censored Samples from the Two-Parameter Weibull Distribution", Accepted for Publication by the Journal of Statistical Planning and Inference.

7. Tallian, T. E., et al. "Rolling Bearing Damage Atlas, A Morphological Atlas," Revere Press, Philadelphia, 1974.

8. Hingley, C. B., "Final Summary Report on A Study of the Effects of Grease Lubricants on the Vibration of Rolling Bearings", U. S. Department of the Navy, Naval Ship Systems Command, Contract N00024-67-C-5403, SKF Report AL68P019 (1968).

9. Anderson, F. W., et al. "Preparation of Grease Specimens for Electron Microscopy", NLGI Spokesman, October 1967, pg. 252.

10. Liu, J. Y., McCool, J. I., Tallian, T. E.,"Dependence of Bearing Fatigue Life on Film Thickness to Surface Roughness Ratio", ASLE Trans., Vol. 17, No. 2, pp. 144-152 (1975).

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