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FILTRATION EFFECTS ON BALL BEARING LIFE AND CONDITION IN A CONTAMINATED LUBRICANT

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ABSTRACT

Ball bearings were fatigue tested with a noncontaminated MIL-L-23699 lubricant and with a contaminated MIL-L-23699 lubricant under four levels of filtration. The test filters had absolute particle removal ratings of 3, 30, 49, and 105 microns. Aircraft turbine engine contaminants were injected into the filter's supply line at a constant rate of 125 milligrams per bearing hour. Bearing life and running track condition generally improved with finer filtration. The experimental lives of 3- and 30-micron filter bearings were statistically equivalent, approaching those obtained with the noncontaminated lubricant bearings. Compared to these bearings, the lives of the 49-micron bearings were statistically lower. The 105-micron bearings experienced gross wear. The degree of surface distress, weight loss, and probable failure mode were dependent on filtration level, with finer filtration being clearly beneficial.

INTRODUCTION

It is generally accepted that rolling-element fatigue failures are a consequence of competitive failure modes developing primarily from either surface or subsurface defects [1-5]. Surface initiated fatigue, often originating at the trailing edge of a localized surface defect, comprises a significant percentage of bearing fatigue failures [3, 6]. This is particularly true in machinery where strict lubricant cleanliness and/or sufficient elastohydrodynamic film thickness are difficult to maintain. However, the failure theory of Lundberg and Palmgren

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[7], the commonly accepted basis for bearing service life ratings, is based only on subsurface originated spalling. Recently, Tallian has published an expanded fatigue life prediction model which considers surface initiated spalling for rolling-element bearings with surface defects [8].

The presence of contaminants in rolling-element lubrication systems can have a large detrimental effect on bearing service life as well as lead to a significant degree of component surface distress. The research of [9] has shown that a 80 to 90 percent reduction in bearing life compared to that as measured in clean oil resulted when ceramic, silica and iron particles were continuously fed into the bearing lubrication system at 12 milligrams per hour. Furthermore, the bearing tests conducted in [10], in which an isolated, "ultraclean," recirculating bearing lubrication system was used, suggest that the use of an "ultraclean" lubrication system in place of a conventionally clean (10 micron filtration) system may improve bearing life several fold.

In rolling-element systems where significant amounts of combined sliding and rolling contact occur, such as for the contact between gear teeth and the cone-rib contact in a tapered-roller bearing [11], the presence of debris in the oil can lead to gross wear damage and premature failure. Experiments performed in [11] on tapered-roller bearings have shown that wear is proportional to the amount of contaminant in the lubricant and that the wear rate generally increases as the contaminant particle size is increased. Furthermore, the wear process will continue as long as the contaminant particle size exceeds the thickness of lubricant film separating the bearing surfaces.

The potential for a drastic reduction in bearing service life due to the presence of contaminants gives great incentive for fine oil filtration, particularly for critical rotating machinery. Until recently filtration levels for aircraft turbine engine lubrication systems have been mainly limited to metallic screens of 100 to 150 mesh (150 to 110 microns) [12]. However this situation seems to be changing. The study performed in [13], in which the production 40-micron nominal main oil filter from a T-53 gas turbine engine lubrication system was replaced by a 3-micron absolute filter, demonstrated some of the advantages of finer filtration. The new filter elements provided a much cleaner lubricant with less component wear, while greatly extending the time between filter removals for clogging and oil changes. This was accomplished with a modest increase in filter size and weight and with a new filter clean pressure drop nearly the same as the original production unit. Recently, 3-micron absolute filtration was selected for use on the T-700 gas turbine engine which power advance helicopters.

Presently there is a scarcity of test data relating the quantitative effects of filter performance on rolling-element component life. The objective of the research reported herein was to quantify the effects of filtration level on the service life and condition of rolling-element bearings which operate in a controlled contaminated lubricant environment.

Fatigue tests were conducted on a multiple bearing fatigue test machine with 65-mm bore diameter, deep-groove ball bearings lubricated with MIL-L-23699 qualified, tetraester oil. Four levels of filtration were investigated utilizing static filters with absolute particle removal ratings of 3, 30, 49, and 105 microns (0.45, 10, 30, and 70 microns nominal). The results of these tests were compared to a controlled baseline series of tests in which no contaminants were added to the test lubricant. Test conditions consisted of a bearing shaft speed of 15 000 rpm, a radial load of 4580 newtons (1030 lb) and an oil in temperature of 347 K (165^{o} F).

TEST BEARINGS, LUBRICANT, FILTERS AND CONTAMINANTS

The test bearings were ABEC-3 grade, deep groove ball bearings with a 65-mm bore diameter, a 90-mm outer diameter, a 13-mm width and contained 18 balls having a 7.94-mm (5/16-in.) diameter. The inner and outer races as well as the balls were manufactured from a single heat of carbon vacuum-degassed (CVD) AISI 52100 steel. The nominal hardness of the races and balls was Rockwell C 62±1.0. The ball retainer was a rivetted, two-piece, machined inner-land riding cage made from iron-silicon-bronze. The raceways were ground to a nominal surface finish of 0.1 micron (4 μin.) rms and the balls to a surface finish of 0.05 micron (2 μin.) rms.

The lubricant utilized for this test program was a 5-centistoke at 372 K (210° F) neopentylpolyol (tetra) ester for which a substantial amount of test data is available [14]. This oil is qualified for use in gas turbine engine lubrication systems under MIL-L-23699 specifications.

All of the test filters used during the course of this study were of porous depth-media construction. Manufacturer's specifications of these commercially available test filters along with the test series number in which they were used are presented in Table 1.

The absolute removal ratings shown in Table 1 were determined by traditional filter test methods per MIL-F-27656. This method uses a known distribution of graduated glass beads which are fed "once through" the test filter to determine the largest pore size of the filter media. (An improved filter performance rating method (ANSI-B93.31-1973) is now being adopted which can determine the filter's particle removal efficiency as a function of particle size in a recirculating lubrication system with continuous test dust addition. This method, based largely on research performed at Oklahoma State University [15, 16], provides useful time dependent filter performance data for recirculating lubrication systems.)

The contaminants used in this study consisted of a mixture of carbon dust, Arizona a test dust, and stainless steel powder. The composition of this contaminant mixture, as listed in Table 2, was similar to the composition of particulate matter found in the lubricant filters of typical aircraft gas turbine engines, based on a field survey of 50 JT8D commercial engines. Analysis of debris from the engine lubrication system showed that up to 90 percent of the particles were carbonaceous in composition with the remainder being primarily siliceous and metallic. To give a physical appreciation of the fineness of the test contaminant mixture in which nearly all of the particles are less than

40 microns in size, the period at the end of this sentence is greater than 500 microns in diameter.

BEARING FATIGUE TESTER

A cross section of the bearing fatigue tester utilized in this investigation is shown in Fig. 1. This tester is described in detail in [17]. Two identical bearing fatigue testers, each containing four test bearings were operated concurrently. Each bearing tester is driven by a quill shaft system connected to the 37.3 kW (50 hp) variable speed drive system (not shown in the illustration). The bearings are loaded only in a radial direction by a hydraulic cylinder. The radial load is transmitted equally to the two center bearings through a wiffletree and is reacted by the two outboard bearings as shown. Thermocouples were mounted to the outer-race of each of the test bearings.

The lubrication supply system, delivers a total of 1090 kg/hr (2400 lb/hr) of oil through the test filter to the eight test bearings. The flow is equally divided among the test bearings by a calibrated orifice at an oil supply pressure of 0.28 MPa (40 psi). Each test bearing was lubricated by its own calibrated oil jet.

From the test bearings the oil gravity drains into a collector pan from where it is returned to the oil supply tank by a scavenge pump. On this return line is an oil-water heat exchanger that regulates the oil in temperature to the bearings at the required 347 K (165^{o} F).

For the contaminated lubricant tests, the test contaminant and replenishment oil are mixed together in an oil slurry form. This slurry was periodically (approximately every 10 min) injected by a hydraulic piston into the test filter lubricant supply line in 12-milliliter quantities, containing approximately 170 milligrams of contaminant. This produced a contamination rate of 125 milligrams of contaminants per hour per bearing or roughly a level teaspoon of contaminant powder every 16 hours.

The test stand instrumentation included an accelerometer system which detected bearing failures as well as protective circuits which shut down the drive system, if any of the test parameters deviate from the programmed conditions Parameters monitored and recorded during the test included bearing inner race speed, oil flow to each tester, test bearing outer race temperature, lubricant supply and scavenge temperature, and bearing vibration level.

RESULTS AND DISCUSSION

Bearing Fatigue Results

Bearings were tested at speeds at 15 000 rpm under a radial load of 4580 newtons (1030 lb) resulting in an inner race maximum Hertz stress of 2410 MPa (350 000 psi). Lubricant supply temperature was maintained at 347 K (165° F). Based on the average outer race temperature of 361 K (190° F), the isothermal elastohydrodynamic film thickness at the inner race contact was 0.373 micron (14.7 μin.) [18]. This resulted in a minimum film thickness to composite roughness ratio of 3.3 which provides full film lubrication [19].

The test study was divided into five test series. In test series I, 32 bearings were fatigue tested to provide baseline data for a clean lubrication system under 49-micron absolute filtration with no contaminants added to the system. The bearing tester was disassembled and flushed clean after every failure. Test series II to V were conducted in the same manner as test series I with the exception that filters of different ratings were installed into the lubrication system (see Table 1) and test contaminants of a prescribed composition (see Table 2) were metered into the lubrication line ahead of the test filter. During all testing, periodic oil samples were taken from the lubrication line downstream of the test bearings and subjected to viscosity, total acid number and particulate oil analyses.

Fatigue life results of the bearings tested were statistically analyzed in accordance with the methods of [20] and are summarized according to lubricant contamination level in Table 3. A summary of their Weibull failure distributions are presented in Fig. 2.

In test series I, nine of the 32 bearings experienced fatigue failure prior to the 2000-hour suspension time. All of the remaining bearings completed the test undamaged except for two early suspensions due to rough operation.

At these test conditions the Anti-Friction Bearing Manufacturers Association (AFBMA) catalog 10-percent life is 47 hours. The experimental 10-percent life of the baseline bearings was 672 hours or more than 14 times the AFMBA predicted life. Using the bearing life adjustment factors of [19], the predicted 10-percent life is increased by a factor of 5.2 to 245 hours, still 2.7 times less than measured.

In comparing the test results shown in Table 3 and Fig. 2, good fatigue lives, approaching those of the noncontaminated lubricant, baseline bearings, were obtained in tests with 3-micron (series II) and 30-micron (series III) absolu filtration in a contaminated lubricant. The experimental lives of bearings tested with these filters were statist cally equivalent. These lives were approximately 80 percent and 40 percent of those of the baseline bearings at the 10-percent and 50-percent life levels, respectively. However, the experimental life differences among these three groups of bearings varied from being statistically insignificant at the 10-percent life level to highly significant at the 50-percent level as indicated by the confidence numbers tabulated in Table 3. The fatigue lives obtained with the test bearings from the 49-micron filter test series (series IV) with a contaminated lubricant were approximately 50 percent and 25 percent of the baseline bearings (series I) 10- and 50-percent lives, respectively.

In tests conducted with 105-micron absolute filtration in contaminated oil, all 16 test bearings experienced excessive wear without prominent spalling within 500 hours of testing. The rivet heads on three of the test bearings failed causing cage separation, presumably due to debris generated high ball-race traction forces and buildup of debris in the ball pockets. It is apparent from the fatigue life results shown in Fig. 2(e) that the life dispersion parameter or Weibull slope steadily increased with coarser filter size. According to the contaminated lubricant, fatigue life model advanced in [8], the Weibull slope should increase for bearings experiencing progressive surface damage while running.

Damage accumulating at a linear rate would be expected to double the slope of rolling-element life associated with bearings which had an unchanging number of preexisting surface defects. Quadratic damage accumulation would be expected to triple the slope. Although it is not possible to accurately assess the damage accumulation rate associated with the various bearing test series, an experimental Weibull slope variation in excess of 3 to 1 was obtained, as listed in Table 3, which lends qualitative support to the fatigue life model of [8].

Effect of Contaminants on Test Bearing Surface Distress and Wear

Post test examination of the raceways of the long-lived, suspended test bearings from test series I, II, and III showed great differences in the degree of surface distress in relation to filtration level. These differences in running track condition are distinctly greater than the differences obtained in fatigue life. Figure 3 shows representative macro and scanning electron microscope (SEM) photographs of test bearing inner races that were suspended from test without fatigue failure. Included for comparison are photos of an untested bearing. It is apparent from these photos that the amount of surface distress and wear progressively increases with coarser filter size. This is reflected by an increase in the intensity and width of the wear track coupled with the increasing absence of grinding marks. The original grinding marks clearly present on both the untested and clean lubricant test bearings are still visible on the bearings from the 3-micron absolute filter tests after nearly 1200 hours of testing but are only faintly visible on bearings tested with the 30-micron filters. The grinding marks on the bearings from the 49- and 105-micron filter tests are completely worn away and only a matted surface remains.

The progressive disappearance of grinding marks with an increase in filter size is indicative of a degradation of the local elastohydrodynamic film thickness. Debris particles breach the clearance between contacting elements causing an interruption of the protective film which in turn leads to surface distress. A loss of film thickness can cause an increase in the tangential shear forces on or near the surface and hasten the onset of surface initiated fatigue failure.

Significant metal-to-metal contact will cause a substantial increase in tractive forces that can lead to plastic flow and microcracking. All of the failed bearings tested with a 49-micron absolute filter in contaminated oil showed evidence of extensive microcracking. The microcrack network on these bearing races would usually coalesce to form multiple patches of shallow micropits. Prominent spalls were generally found within these patches of micropits. Figure 4 shows a typical surface initiated fatigue spall from test series IV (49 micron absolute filter) which emanated in this manner.

In conjunction with the observed increase in bearing surface damage with filter size is an increase in bearing average weight loss of the suspended test bearings as listed in Table 4. On the basis of grams per 100 test hours the suspended bearings tested with 3-, 30-, 49-, and 105-micron absolute filters had, respectively, 1.9, 3.2, 4.2, and 89 times the weight loss of the suspended baseline bearings tested with uncontaminated oil. It is instructive to note from Table 4 that failed test bearings generally experienced a weight loss several times that of a suspended bearing. This factor became a reliable means of selecting the failed bearing or bearings from those unfailed without resorting to bearing disassembly.

The observed increase in surface distress with filter size is a direct consequence of the number and size of debris particles suspended in the oil passing through the test bearing contacts. Particulate counts were made on oil samples taken periodically at a point downstream of the test bearings. A summary of the particle count readings for the various test series can be found in Table 5. Excluding occasional inconsistencies, the particle count readings showed a trend of decreasing particle levels with finer filtration. In addition, the debris levels show, for the most part, no significant increases with time. This indicates that the filter was performing stably and the debris generation rates associated with the bearings were relatively constant. Comparison of particle count readings obtained during these tests with those taken during contaminant injection system calibration where the test filter was not installed, indicated that the test filters were performing efficiently. Except for the 105-micron absolute filter, all test filters prevented greater than 99 percent of the incoming particles that were 5 microns or larger from reaching the test bearings.

Bearing Failure Examination

Metallurgical examination of the test bearing failures were made with the intent of determining the origin of the failure. In most cases, direct evidence of a surface defect initiated spall was eradicated by spall propagation and/or camouflaged by secondary spall debris damage. In several cases where the bearings were suspected of subsurface initiated failure, metallographic cross sections were made through the spall area. These examinations failed to uncover any metallurgical anomalous conditions such as faulty microstructure, nonmetallic inclusions or carbide agglomeration which would conclusively verify subsurface origin. Microscopic examination of the shape and depth of the spall generally gave the best indication of the most probable failure mode.

Many of the incipient spalls on failed bearings from the baseline, noncontaminated lubricant test series were elliptically shaped, relatively deep and steep sloped, giving the appearance of being subsurface initiated. Examination of the spalls from the other test series with a contaminated lubricant revealed that fatigue failures were both surface and subsurface initiated with a trend toward more surface initiated spalls with an increase in filter size. Also the mechanism of surface spall initiation appeared to shift with filter size. Point surface originated spalls, characterized by a shallow, arrow-head patterned spall [2, 3], appeared to be the most prevalent in the case of the 3-micron absolute filter tests. Micropitting, the result of debris particles interrupting the elastohydrodynamic film, was the most prevalent in tests with 49-micron filtration as described earlier.

Occasionally debris dents significantly larger than the "absolute" pore size of the filter were found on suspended test bearings, indicating the debris particles can be generated within the bearing assembly itself. However, the number of these particles and their potential to initiate fatigue is judged relatively small in comparison to debris ingested externally or generated within the lubrication system and not removed by the filter. Therefore, to provide maximum component life, a concerted effort must be made to prevent contaminants from gaining entry into the system through proper sealing and secondly, to provide an effective means of removing particles that have become suspended in the oil through fine filtration.

SUMMARY

Fatigue tests were conducted on groups of 65-mm bore diameter deep-groove ball bearings with a noncontaminated MIL-L-23699 lubricant and with a contaminated lubricant under four levels of filtration. The noncontaminated lubricant test series, which provided baseline data, used prefiltered oil in a recirculating lubrication system containing a 49-micron absolute (30-micron nominal) full flow filter. In the remaining series of tests, contaminants, of a composition similar to that found in filters from aircraft gas turbine engines, were injected into the test filter's supply line at a constant rate of 125 milligrams per hour per bearing. The test filters, of porous depth media construction, had absolute particle removal ratings of 3, 30, 49, and 105 microns (0.45, 10, 30, and 70 micron nominal), respectively. Test conditions included a bearing shaft speed of 15 000 rpm, a radial load of 4580 newtons (1030 lb) producing a maximum Hertz stress of approximately 2410 MPa (350 000 psi) on the bearing inner race. The temperature of the lubricant into the test bearing and the sump temperature were maintained at 347 K (165° F). The following results were obtained.

1. Bearing running track condition and fatigue life, to a lesser extent, generally improved with finer filtration. Tests with the baseline noncontaminated lubricant bearings produced the longest fatigue lives. Differences in the 10-percent lives of these bearings and those in contaminated lubricant tests with 3- and 30-micron absolute filtration were statistically insignificant, but were statistically significant for the bearing tested with a 49-micron absolute filter.

2. Surface distress and wear of the test bearings' running track markedly increased with coarser filter size. Gross wear of bearings tested with a 105-micron absolute (70-micron nominal) filter precluded the onset of rolling-element fatigue.

3. The bearing life dispersion parameter of Weibull slope increased with coarser filtration.

4. Fatigue failures were both surface and subsurface initiated with a trend toward more surface initiated failures with coarser filtration. All of the failed bearings tested with 49-micron absolute filtration in a contaminated lubricant exhibited evidence of micropitting and surface initiated failure.

REFERENCES

1. Littmann, W. E., and Moyer, C. A., "Competitive Modes of Failure in Rolling Contact Fatigue," presented at Automotive Engineering Contress, Detroit, Mich., Jan. 14-18, 1963, SAE Paper No. 620A.
2. Littmann, W. E., and Widner, R. L., "Propagation of Contact Fatigue from Surface and Subsurface Origins," J. Basic Eng., ASME Trans., 88, Ser. D (3), 624-636 (1966).
3. Martin, J. A., and Eberhardt, A. D., "Identification of Potential Failure Nuclei in Rolling Contact Fatigue," J. Basic Eng., ASME Trans., 89 Ser. D (4), 932-942 (1967).
4. Chiu, Y. P., Tallian, T. E., and McCool, J. I., "An Engineering Model of Spalling Fatigue in Rolling Contact, I. The Subsurface Model," Wear, 17, 433-446 (1971).
5. Tallian, T. E., and McCool, J. I., "An Engineering Model of Spalling Fatigue Failure in Rolling Contact, II. The Surface Model," Wear, 17, 447-461 (1971).
6. Tallian, T. E., "Prediction of Rolling Contact Fatigue Life in Contaminated Lubricant: Part II - Experimental," J. Lubr. Tech., ASME Trans., 98, Ser. F (3), 384-392 (1976).

7. Lundberg, G., and Palmgren, A., "Dynamic Capacity of Rolling Bearings," Ing. Vetansk. Akad. Handl., No. 196 (1947).

8. Tallian, T. E., "Prediction of Rolling Contact Fatigue Life in Contaminated Lubricant: Part I - Mathematical Model," J. Lubr. Tech., ASME Trans., 98, Ser. F (2), 251-257 (1976).

9. Okamoto, J., Fujita, K., and Yoshioka, T., "Effects of Solid Particles in Oil on the Life of Ball Bearings," J. Mech. Eng. Lab. (Tokyo), 26 (5), 228-238 (1972). (NASA Technical Translation; NASA TT F-15,653; June 1974).

10. Dalal, H., Cotellesse, G., Morrison, F., and Ninos, N., "Final Report on Progression of Surface Damage in Rolling Contact Fatigue," SKF-AL74T002, SKF Industries, Inc., Feb. 1974. (AD-780453)

11. Fitzsimmons, B., and Clevenger, H. D., "Contaminated Lubricants and Tapered Roller Bearing Wear," ASLE Trans., 20 (2), 97-107 (1977).

12. Craig, W. R., "Gravimetric Determination of Sediment in Turbine Engine Oils," Air Force Aero Propulsion Laboratory, AFAPL-TR-75-32, July 1975. (AD-A014340)

13. Lynch, C. W., and Cooper, R. B., "The Development of a Three-Micron Absolute Main Oil Filter for the T53 Gas Turbine," J. Lubr. Tech., ASME Trans., 93, Ser. F (3), 4[illegible]-436 (1971).

14. Signer, H., Bamberger, E. N., and Z[illegible]retsky, E. V., "Parametric Study of the Lubrication of Thrust Loaded 120-mm Bore Ball Bearings to 3 Million DN," J. Lubr. Tech., ASME Trans., 96, Ser. F (3), 515-526 (1974).

15. Fitch, E. C., "The Multi-Pass Filter Test-Now A Viable Tool," 8th Annual Fluid Power Research Conference, Stillwater, Oklahoma, 1974, Paper No. P74-39.

16. Fitch, E. C., "Measuring Contaminant Tolerances in Terms Compatible with Filtration Specifications - New Research Findings," 1975 Symposium on Contamination Control to Benefit Man and Product, Gothenburg, Sweden, April 2-4, 1975, Paper No. P75-6.

17. Loewenthal, S. H., Moyer, D. W., and Sherlock, J. J., "Effect of Filtration on Rolling-Element Bearing Life in a Contaminated Lubricant Environment," proposed NASA TP.

18. Cheng, H. S., "A Numerical Solution of the Elastohydrodynamic Film Thickness in an Elliptical Contact," J. Lubr. Tech., ASME Trans., 92, Ser. F (1), 155-162 (1970).

19. Bamberger, E. N., Harris, T. A., Kacmarsky, W. M., Moyer, C. A., Parker, R. J., Sherlock, J. J., and Zaretsky, E. V., "Life Adjustment Factors for Ball and Roller Bearings - An Engineering Design Guide," ASME, New York, 1971.

20. Johnson, L. G., "The Statistical Treatment of Fatigue Experiments," General Motors Corp., GMR-202, 1956.

TABLE I. - TEST FILTER SPECIFICATIONS

Test series[a]	Removal ratings, μ		
	Nominal[b]	Mean	Absolute[c]
I	30	40	49
II	.45	.9	3.0
III	10	20	30
IV	30	40	49
[d]V	70	N/A	105

[a]Test series I used clean oil, in all others contaminants were added.

[b]MIL-F-5504.

[c]MIL-F-27656.

[d]Sintered square weave stainless steel, wire cloth filter media, all others resin impregnated organic/inorganic fibers.

TABLE 2. - TEST CONTAMINANT COMPOSITION

Constituent	Parts per mixture by weight	Particle distribution
Stainless steel particles	1	100 percent less than 44 microns
Arizona coarse test dust	10	12 percent less than 5 microns 24 percent less than 10 microns 38 percent less than 20 microns 61 percent less than 40 microns 91 percent less than 80 microns 100 percent less than 200 microns
Carbon-graphite test dust	80	75 percent less than 10 microns 92 percent less than 20 microns 100 percent less than 40 microns
Total contaminant mixture	91	70 percent less than 10 microns 86 percent less than 20 microns 96 percent less than 40 microns 4 percent greater than 40 microns

TABLE 3. - FATIGUE-LIFE RESULTS OF 65 MILLIMETER BORE BALL BEARING TESTS

FOR VARIOUS LEVELS OF FILTRATION IN A CONTAMINATED LUBRICANT

[Radial load, 4580 N (1030 lbf); speed, 15 000 rpm; temperature, 347 K (165° F); test lubricant, MIL-L-23699 type.]

Test series[a]	Test filter absolute rating, μ	Experimental hours		Weibull slope	Failure index[b]	Confidence number,[c] percent	
		10-percent life, L_{10}	50-percent life, L_{50}			10-percent life	50-percent life
I	49	672	2276	1.54	9 out of 32	--	--
II	3	505	993	2.78	10 out of 16	63	99
III	30	594	857	5.12	11 out of 16	57	99
IV	49	367	533	5.06	20 out of 32	89	99
[d]V	105	---	---	----	----------	--	--

[a]Test series I used clean oil, in all others contaminants were added.

[b]Number of fatigue failures out of number of bearings tested.

[c]Probability expressed as a percentage that the fatigue life in the contaminated lubricant test series will be less than the life with the clean oil in test series I.

[d]Test series V was suspended after 448 test hours on each of the test bearings due to excessive bearing wear. No fatigue failures were encountered.

TABLE 4. - TEST BEARINGS AVERAGE WEIGHT LOSS

Test series[a]	Test filter absolute rating, μ	Suspended test bearings		Failed test bearings	
		gm/brg	gm/100 hr	gm/brg	gm/100 hr
I	49	0.0412	0.0031	0.2775	0.0311
II	3	.0548	.0059	.3157	.0390
III	30	.0806	.0100	.1679	.0214
IV	49	.0809	.0130	.3288	.0713
[b]V	105	1.0204	.2757	-----	-----

[a]Test series I used clean oil, in all others contaminants were added.

[b]All bearings from test series V suspended due to heavy wear.

TABLE 5. - SUMMARY OF REPRESENTATIVE PARTICLE COUNT READINGS

[Samples taken downstream of test bearings.]

Test series	Test filter absolute rating, μ	Test time, hr	Particle count, 10^3 particles/100 ml				
			Micron size range				
			5-15	16-30	31-50	51-100	>100
Calibration[a]	---	8	287 000	26 700	3 400	187	19.2
		22	969 000	89 100	16 000	462	39.1
I[b]	49	139	25.0	4.6	1.8	0.4	0.2
		417	23.8	7.1	3.0	0.5	0.2
		1207	80.0	11.1	0.2	0.2	0.2
II	3	12	129	7	0.7	0.3	0.2
		785	145	9	2.7	0.5	0.3
		876	102	6	1.9	0.4	0.3
III	30	158	70	8	4.8	1.1	0.6
		170	152	15	12.5	1.5	1.0
		676	105	19	10.9	2.5	1.7
IV	49	205	1732	79	3.6	0.4	0.2
		412	255	19	6.8	1.0	0.2
		663	605	38	8.8	1.2	0.4
V	105	116	116 900	4 870	287	133	48.2
		202	221 100	5 490	549	79	20.5

[a]Contaminant injected into system at 3.1 mg/100 ml/hr without filter and test bearings installed.

[b]Test series I used clean oil, in all others contaminants were added.

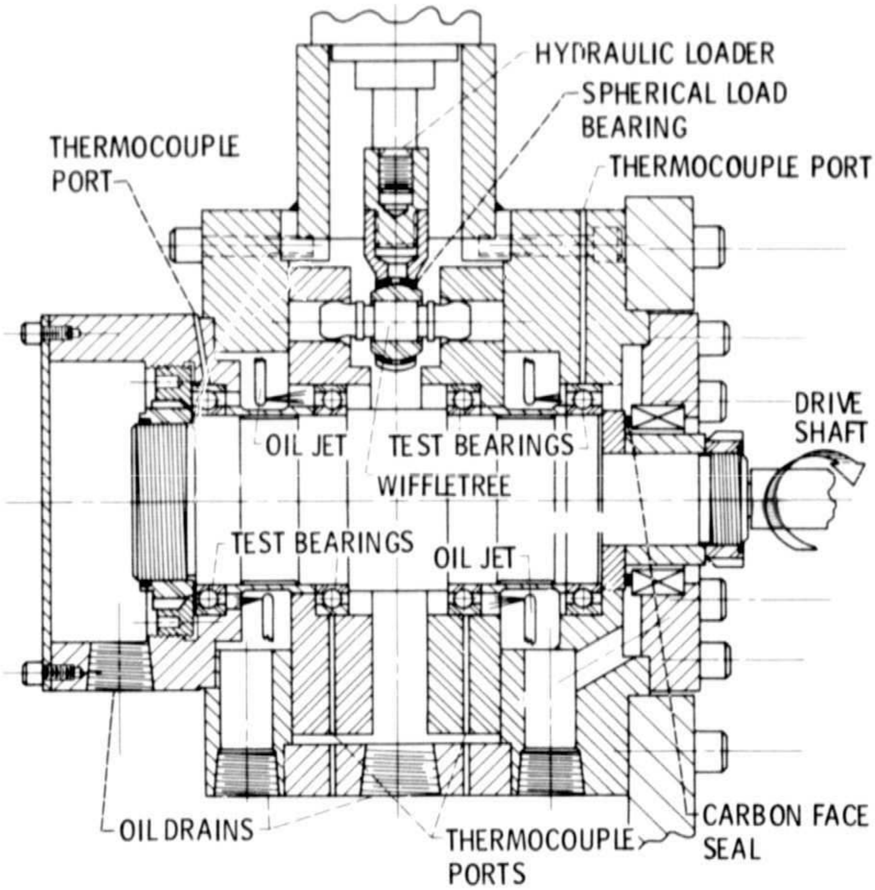


Figure 1. - Bearing fatigue tester.

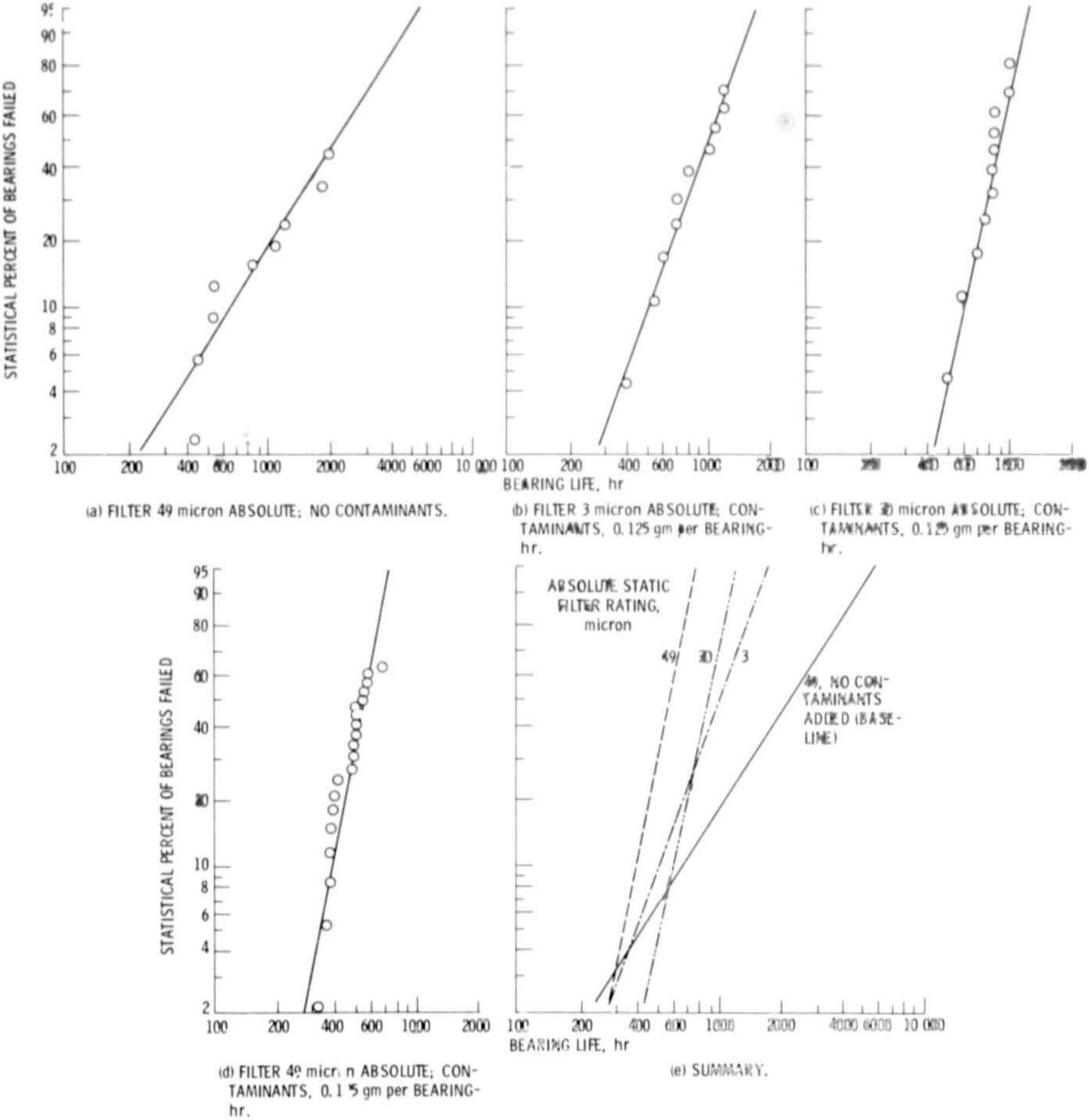
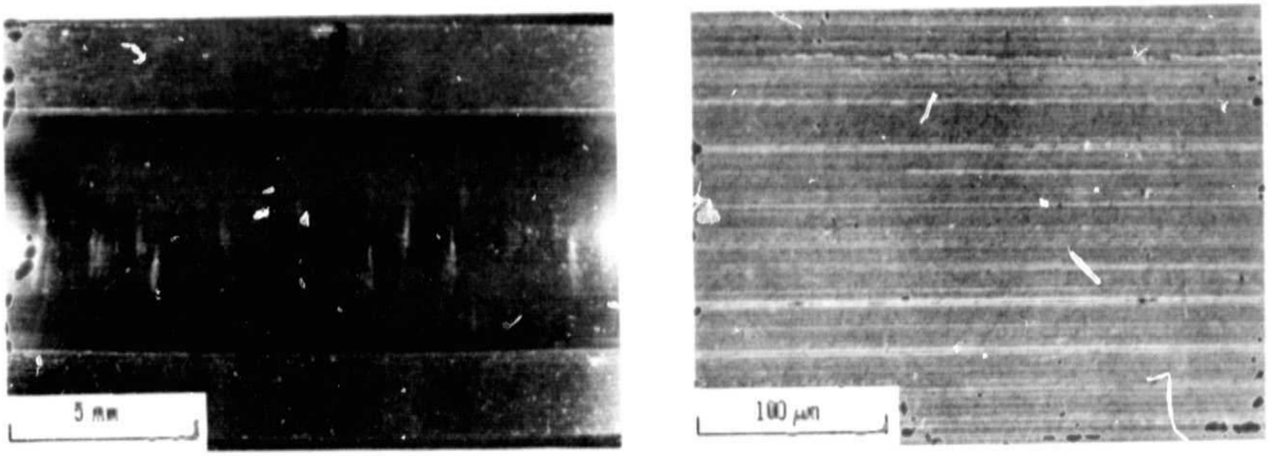
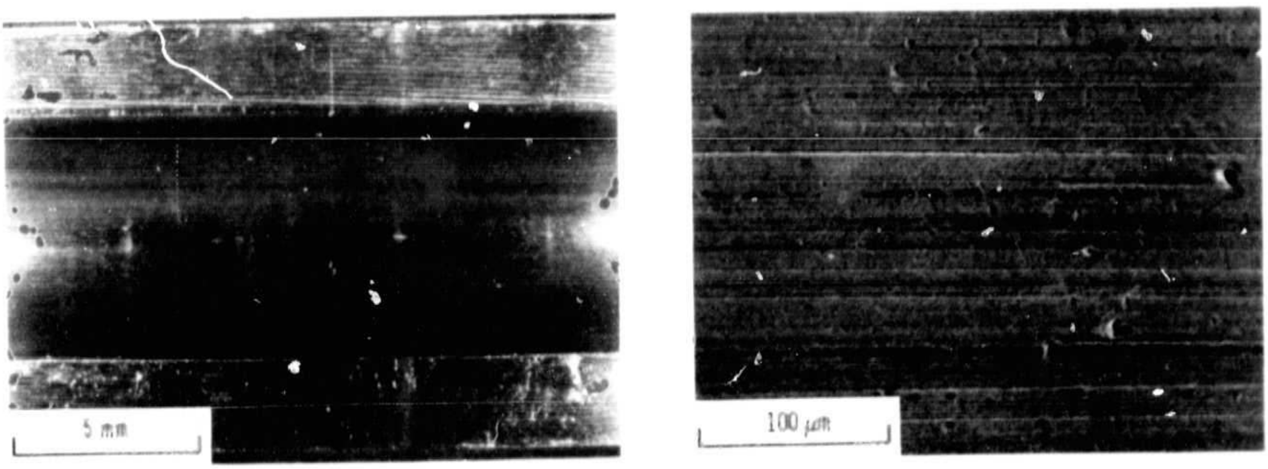


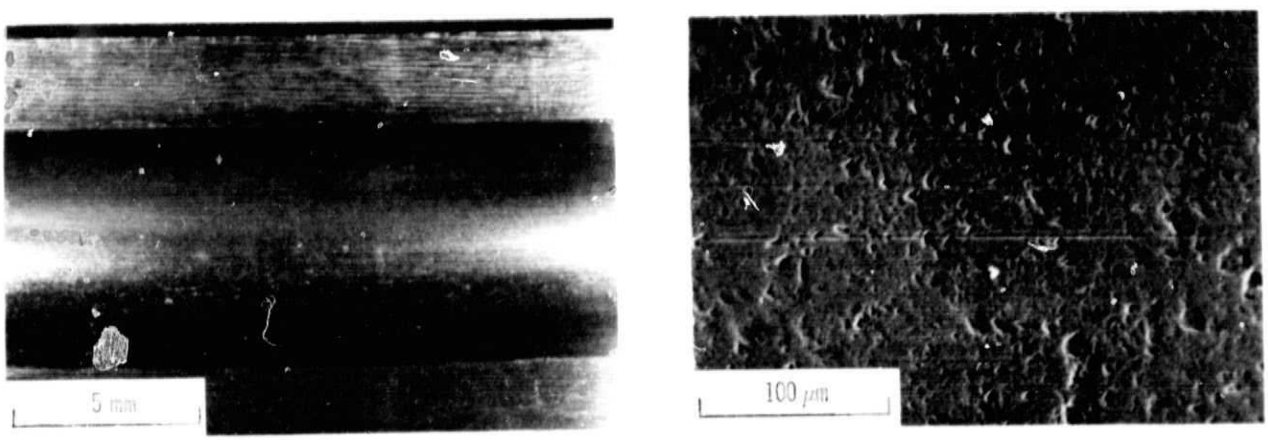
Figure 2. - Effect of filtration level on 65 mm bore ball bearing fatigue life in a contaminated lubricant. Speed, 15 000 rpm; lubricant MIL-L-23699.



(a) Untested test bearing.

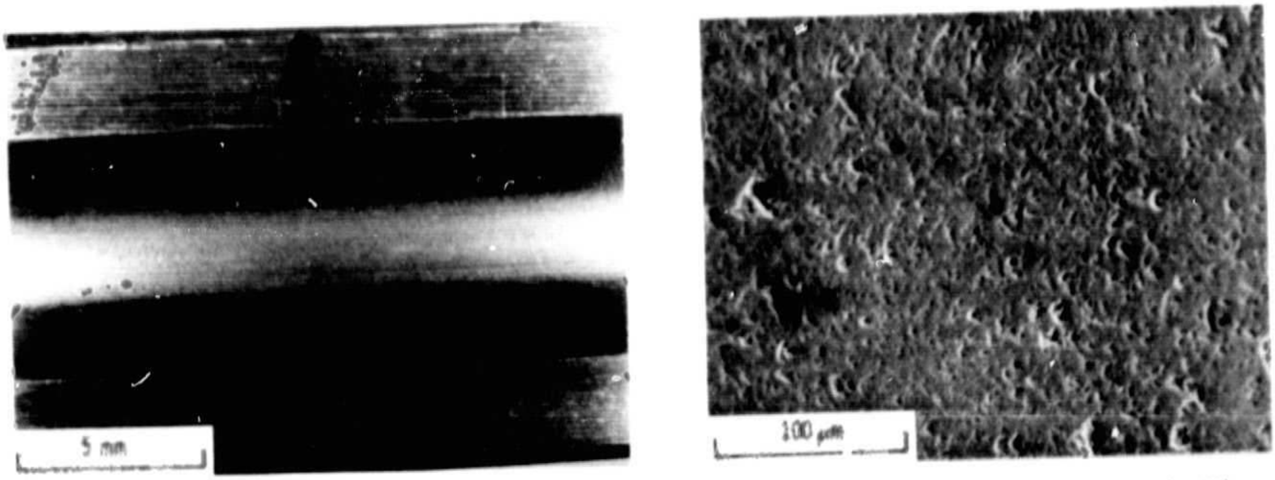


(b) Test bearing suspended after 1206 hours from 49-micron-absolute filter tests with clean lubricant (test series I).

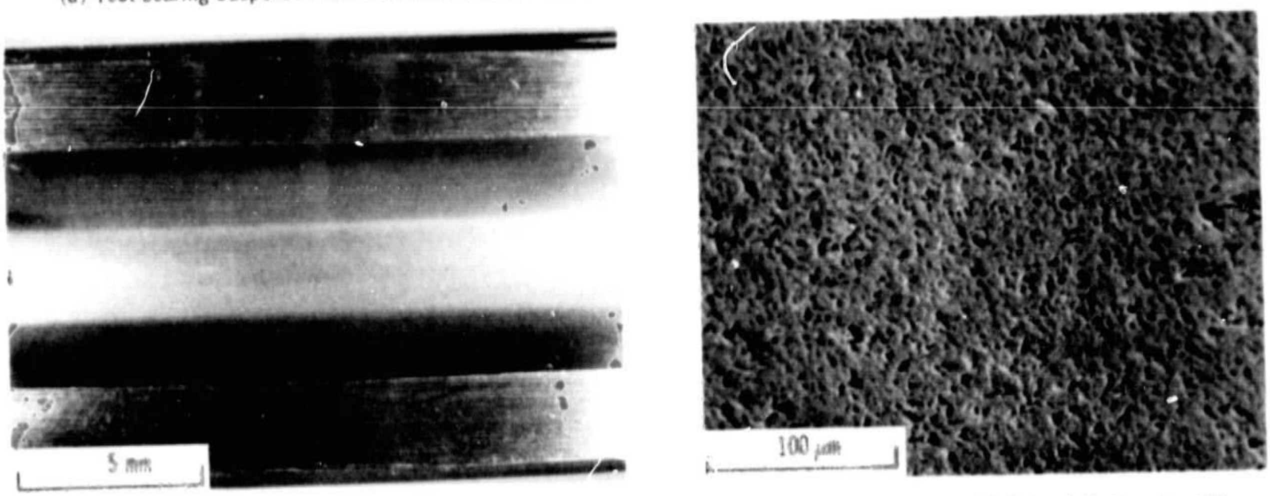


(c) Test bearing suspended after 1172 hours from 3-micron-absolute filter tests with contaminated lubricant (test series II).

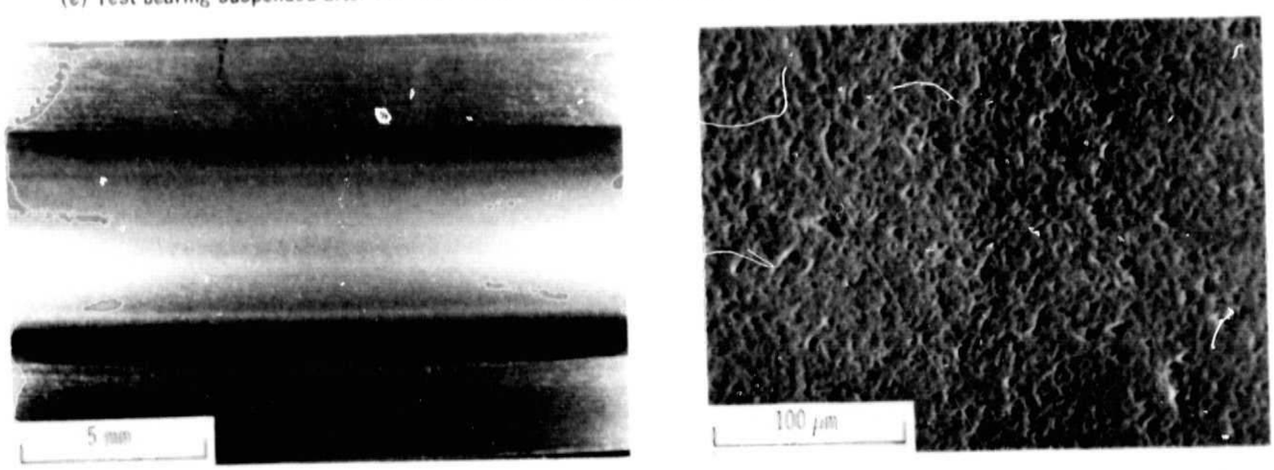
Figure 3. - Macro and SEM photos of test bearings inner race showing progressive surface damage of running track with coarser filter size.



(d) Test bearing suspended after 987 hours from 30-micron-absolute filter tests with contaminated lubricant (test series III).

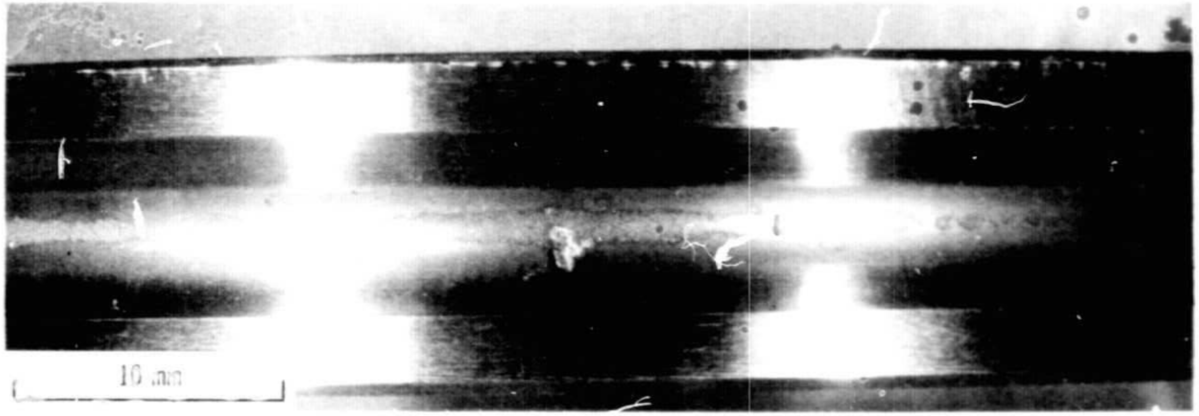


(e) Test bearing suspended after 663 hours from 40-micron-absolute filter tests with contaminated lubricant (test series IV).

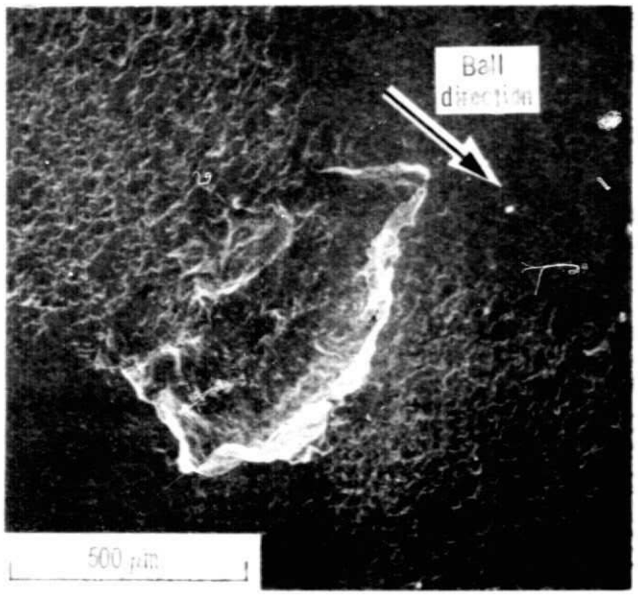


(f) Test bearing suspended after 449 hours from 105-micron-absolute filter tests with contaminated lubricant (test series V).

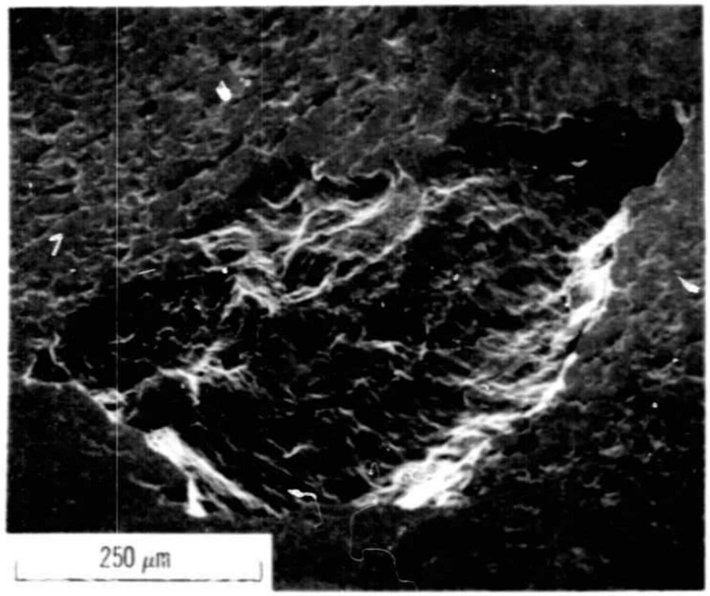
Figure 3. - Concluded.



(a) Inner race, large and small spalls pictured. Frosted area is comprised of vast network of microcracks suggesting collapse of local lubricating film.



(b) Small spall under medium magnification.



(c) Small spall under high magnification.

Figure 4. - Typical surface damage initiated fatigue spalls on bearings operated in contaminated oil with 49-micron-absolute static filter (test series IV). Running time, 327 hours. Note network of microcracks contributing to propagation of multiple spalls.