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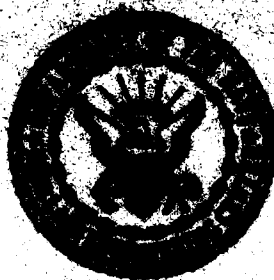
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**WEAR DEBRIS ANALYSIS OF GREASE
LUBRICATED BALL BEARINGS**

Advanced Technology Office
Support Equipment Engineering Department
Naval Air Engineering Center
Lakehurst, New Jersey 08733

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) An investigation was conducted to experimentally determine the wear surface condition of grease-lubricated ball bearings, by monitoring the wear debris retained in the grease. Testing of six bearings was performed on endurance test machines with grease sample removal. Visual and scanning electron microscope examinations of the bearing surfaces were performed per an established schedule by SKF. Respective grease samples were treated, analyzed, and correlated by NAVAIRENGCEN.		

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A total of four bearings failed during the testing while the remaining two bearings reached time up. The testing, therefore, provided a good distribution of failed and unfailed bearings from which the evaluation of bearing failure or imminent failure detection by wear debris analysis could be established.

The results of the wear debris analysis, performed by NAVAIRENGCEN compared to the physical examination of the bearings performed by SKF, showed a good correlation, in terms of monitoring the wear state/condition of the bearings throughout their life. As it appears presently, this analysis technique is best suited to the examination of used grease obtained from dismantled grease lubricated components or in design applications.

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SUMMARY

The purpose of this program was to experimentally investigate criteria relating characteristic grease-lubricated ball bearing failure progression to the quantity and morphology of bearing wear debris in grease samples taken from the bearings. The testing, sample removal, and optical and scanning electron microscope examination was performed by SKF Industries, Inc., and the debris analysis using the Ferrography method was performed by the Naval Air Engineering Center (NAVAIRENGCEN), Lakehurst, New Jersey.

A total of three sets of two 6309 deep-groove ball bearings each were tested and inspected for failures. All testing was sustained until one of the following occurred: (a) a failure of both bearings was experienced as indicated by an increase in bearing vibration level, (b) a lubrication-initiated failure was experienced as indicated by the temperature rate of increase monitor, or (c) a bearing life of 230 million inner ring revolutions was achieved without failure.

The schedule for removing grease samples and inspecting the bearing was different for each set. Set I was run uninterrupted until a failure or time up occurred before removing grease samples and inspecting the bearings. The testing of Set II bearings was interrupted after operating for 1, 5, 10, 20, 52, 80, 120, 160, and 230 million revolutions and/or after failure to remove grease samples. The bearings were not inspected until test termination. The testing of Set III bearings had scheduled interruptions for both sample removal and bearing inspection at the periods specified for Set II bearings.

The testing conditions consisted of the following:

Test Rig - SKF Industries' R2 Endurance Testers

Test Bearing - SKF 6309 Deep Groove Ball Bearing

Lubrication - 12.6 Grams of Amoco Super MIL-Grease A72832 (MIL-G-23827) Load - 2,600 pounds Radial (C/P = 3.5)

Theoretical Bearing L_{10} Life - 43 Million Revolutions

Test Speed - Inner Ring Rotation at 5,500 rpm

Test Time Up - 230 Million Revolutions - 708 Hours (Essentially Equivalent to the Theoretical L_{50} Life)

Bearing Material - Carbon vacuum deoxidized (CVD) 52100 steel.

The testing, grease sample removal, and bearing inspection was successfully completed. A total of four bearings failed (two spall failures and two inadequate lubrication failures) during the testing while the remaining two bearings reached time-up. In addition to the four bearings that failed, one of the time-up bearings was not suitable for further operation, i.e., failure was imminent. The testing, therefore, provided a good distribution of failed and unfailed bearings from which the evaluation of bearing failure or imminent failure detection by wear debris analysis could be established.

The resulting grease samples were analyzed by the NAVAIRENGCEN, utilizing the Ferrography technique. The analysis of the grease-retained wear debris necessitated the development of a technique to reduce the grease samples to a condition where they were compatible with the Ferrography technique. A major achievement was the successful application of dissolving the grease utilizing a solvent mixture which produced specimens that equalled the quality of those achieved in oil analysis.

The grease samples collected by SKF were from four areas of the test bearings, namely inner ring, ball/cage area, outer ring, and shield. Ferrograms were made from all grease samples where possible. The prime analysis characteristics of the resulting ferrograms consisted of the morphology of the various wear-debris types, their frequency, and gross size distribution. This data was trended for all six bearings, with an assessment of the bearing life/condition based on these trends.

The results of the wear-debris analysis, performed by the NAVAIRENGCEN, as compared to the physical examination of the bearings performed by SKF, showed a good correlation in terms of monitoring the wear state/condition of the bearings throughout their life. However, the technique as it presently exists appears to be more applicable as a design tool as opposed to a diagnostic/monitoring technique.

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I. INTRODUCTION

A. Extensive research has been performed at the Naval Air Engineering Center's (NAVAIRENGCEN's) Tribology Laboratory in a concerted effort to effectively develop viable techniques in the field of mechanical system health monitoring. Major emphasis has been placed on utilizing several select techniques to correlate wear debris characteristics to component surface wear state/condition. This correlation effort has revealed four critical parameters as being most indicative of the component wear state/condition; namely debris concentration, particle size distribution, elemental composition, and morphology.

B. The monitoring of the above-mentioned wear debris parameters in oil-lubricated systems has been considered under numerous research efforts. However, many wearing components are lubricated with grease, such as gears, cams, splines, and bearings. Presently, there exists no method for evaluating or examining samples of used grease. The purpose of this study was to experimentally investigate the feasibility of determining the wear state/condition of a grease-lubricated component, by monitoring the grease-retained wear debris.

C. The long-range goal of this experimental program is to investigate means by which the incidence of unexpected greased-bearing failures can be reduced in the field by monitoring the debris content of the grease. In this manner, the extent of the damage to bearing parts could be established without completely disassembling the equipment, and bearing replacements could be completed when necessary rather than on a periodic basis. Such a monitoring method should significantly increase equipment reliability, increase equipment availability by reducing the number of required overhauls, and produce a sizable reduction in recurring maintenance costs. It is also known that bearings can be damaged during disassembly and assembly operations. By reducing the overhaul frequency, the danger of damage from handling will be reduced, thus further increasing the reliability of the bearings.

D. In a grease-lubricated bearing, there are three primary conditions in which a bearing failure can occur:

1. Contamination of the bearing by foreign material. Contamination can result in corrosion and/or heavy debris denting of the components. Both corrosion and denting can greatly affect the service life of the bearing. The effect of debris denting was dramatically shown in a recent test program performed for the Navy (reference(a)) where ball bearings, operated in 3 um filtered oil, ran 40 times their calculated L_{10} life.

Ref: (a) Dalal, H.M., et al. "Progression of Surface Damage and Oil Wear Debris Accumulation in Rolling Contact Fatigue", SKF Report AL75T007, April 1975.

2. Inadequate or marginal lubrication resulting from the depletion of the grease or the inability of the oil in the grease to bleed into the bearing contact areas at a sufficient rate. Inadequate or marginal bearing lubrication results in a higher operating temperature and a greatly accelerated wear rate, produced by greater metal-to-metal contact and increased friction. This condition, if allowed to exist, will produce failures due to surface-initiated spalls or a thermal imbalance condition between the rings which could cause the bearing to seize.
3. Classical fatigue spalling which results from the cyclic loading of the bearing elements. It is this method of failure on which the theoretical L_{10} life of a bearing is based.

E. This program was designed to obtain data on one possible method of detecting the initiation of a greased bearing failure/wear condition: the monitoring of grease samples for retained wear debris. In this manner, background data would be accumulated which could be utilized to develop criteria for the prediction of the initiation of bearing failures. Concurrently, meaningful grease sampling techniques would be developed for both laboratory use and field application in the NAVAIRENGCEN's overall tribology program.

F. The program consisted of the testing of three pairs of grease lubricated bearings. The first set was run continuously to a time-up life of 230×10^6 cycles or until a grease or bearing failure occurred. Post-test analysis of the grease and bearing surface was performed to correlate the concentration, size, and morphology of wear debris contained in the grease with the extent of bearing surface wear. In contrast, grease samples were periodically taken for wear debris content analysis throughout the testing of the second set of bearings and detailed inspection of the bearings' surfaces performed following test termination. The third set of bearings was degreased, disassembled, inspected and regreased periodically throughout the test in order to correlate wear debris with progressive bearing surface damage.

G. The analysis of retained wear debris in the grease necessitated the development of a solvolytic technique to reduce the grease matrix to a condition usable for particle separation. The separation process was achieved by utilizing a magnetic separation technique and deposition process. The resulting deposits were then analyzed and compared with the analysis obtained from the physical surface examination of the bearing.

H. The bearing testing, grease sampling, and physical inspection of the bearings was performed by SKF Industries, Inc. (reference(b)). The grease sample preparation, separation, and wear debris analyses were performed by the NAVAIRENGCEN Tribology Laboratory.

Ref: (b) NAVAIRENGCEN Report NAEC-92-133 of August 1979: "Failure Progression Monitoring by Wear Debris Analysis in Grease Lubricated Bearings," Prepared by SKF Inc., under Contract No. N68335-77-C-0584.

II. EQUIPMENT AND TEST PROCEDURES

A. GENERAL DISCUSSION.

1. If a rolling contact bearing is correctly manufactured, mounted, lubricated, maintained free of external contamination, and otherwise properly handled, all causes of failure are essentially eliminated except one: fatigue of the material. The life of an individual bearing is defined as the number of revolutions, or hours of operation at a constant speed, which the bearing is capable of running before the first evidence of fatigue develops in the material of either ring or any of the rolling elements.

2. The life of a group of bearings requires a more specific definition because, when a number of identical bearings are run under the same conditions of load and speed, there is a dispersion of their lives.

3. The "rating life" or briefly "life" of a group of bearings is defined by the Anti-Friction Bearing Manufacturing Association (AFBMA) as the number of millions of revolutions at a given speed that 90 percent of the bearings will complete or exceed before the first evidence of fatigue develops. The symbol L_{10} has been designated to represent the group life value. The symbol L_{50} represents the life which 50 percent of a group of bearings will complete or exceed (median life).

4. Extensive testing by SKF and other companies, together with extensive theoretical research, has shown that within a reasonable degree of accuracy, the fatigue life is inversely proportional to the third power of radial load applied to a ball bearing. Thus the equation $L_{10} = (C/P)^3$ expresses the rated life of a group of bearings when P is the equivalent applied load and C is the dynamic capacity, that is the load which will give a life of one million revolutions. The numerical value of C in pounds for a specific bearing size and type is provided in bearing catalogs.

5. In establishing a test program, as the one reported here, it is important to select an applied load and operating speed such that bearing failures will occur within a given time frame to minimize testing expenses and still obtain the desired information. Therefore, for this program an applied load of 2,600 pounds ($C/P = 3.5$) was selected which results in a calculated L_{10} life of 43 million revolutions for the 6309 test bearing which has a basic load rating of 9120 pounds. The L_{50} life of the group of test bearings was calculated to be 230 million revolutions which was also selected to be the time-up life of the test to insure the fatigue failure of several bearings.

6. An inner-ring rotational speed or shaft speed of 5,500 rpm was selected to limit the operating test period of a given test bearing to 708 hours. Consideration in selecting the speed was also given to the expected outer-ring operating temperature rise which would occur. Experience obtained in prior tests using the same load indicated that the expected temperature rise would be between 77°C and 90°C. This was considered to be reasonable and would not impose excessive restrictions on the selection of the grease.

B. TEST MACHINE. All testing was conducted using SKF-developed R2-type bearing endurance testers. A drawing of the overall tester is presented in Figure 1, and a detailed drawing of a test head is presented in Figure 2.

1. Each machine is comprised of a symmetrical horizontal arbor supported on two cylindrical roller bearings (load bearing) which in turn are supported in split main housings. Labyrinth seals are located on both sides of the load bearings to minimize the escape of the recirculating oil supplied to the bearing for lubrication and cooling. Two test bearings (type 6309) are press fit on the arbor, one at each end, and support a teardrop shaped housing through which the radial load is applied by a deadweight lever arm system. The test bearings are encapsulated by two rings, which form a labyrinth seal on the inboard side of the bearing, and a face plate on the outboard side. Two metal shields are located, one on each side of the bearing, to further minimize the ingestion of external debris and retain the grease and bearing wear particles in the bearing.

2. The test shaft is belt driven by a 15-HP, constant-speed AC motor through pulleys selected to provide the desired test speed. The load bearings are splash lubricated with oil supplied from a central recirculating system at a rate sufficient to control the bearings' operating temperatures. The recirculating oil system contains a 25-micron flow filter.

3. Two methods of detecting imminent bearing failure or the beginning of a bearing failure were incorporated in this program to prevent catastrophic failures which would generate excessive debris. This would render the results of the testing meaningless with respect to the desired goal of determining an imminent failure or the beginning of a failure by examining the size, shape, and quantity of bearing generated debris retained in samples of the used grease.

a. The test bearings' outer ring operating temperatures are sensed by shielded thermocouples and monitored by a Data General NOVA mini-computer control system. This system constantly scans all of the analog input points and an individual point is examined at a minimum rate of once every two seconds. The computer is programmed to turn the drive motor off whenever an outer ring temperature of 120°C is sensed or when the outer ring temperature increases at a rate equal to or greater than 1.1°C per minute for a period of time resulting in a 11.7°C cumulative increase. In addition, the test bearing temperature measured at each 12-minute interval is stored in the computer and printed out each 8 hours to provide a hard-copy log of the thermal history of each test bearing.

b. A vibraswitch, attached to the main housing, monitors the general vibration level of the machine and turns off the drive motor when a significant increase, typical of a bearing failure, occurs.

C. TESTING AND BEARING PREPARATION AND INSPECTION PROCEDURE. The following procedure was used in preparing and mounting the test bearings, grease sampling, and inspecting the test bearings. Bearing Set I refers to the 2 bearings numbered 01 and 02 which were run to a failure or to a time-up of 230×10^6 inner ring rotations. Set II refers to the 2 bearings numbered 03 and 04 from which grease samples were removed at the accumulations of 1, 5, 10, 20, 52, 80, 120, 160, and 230 million revolutions. Set III refers to the 2 bearings numbered 05 and 06 which were removed from the tester, all grease removed and the contacting surfaces of the bearings inspected at intervals specified for bearing Set II.

1. INITIAL MARKING AND CLEANING OF BEARINGS.

a. All test bearings (type 6309 manufactured from carbon-vacuum deoxidized (CVD) 52100 steel) were disassembled and the rings numbered in sequence using an electric etching pencil.

b. The outer and inner rings, cages, and shields of Set II bearings were divided in 16 equal segments and marked with the electric etcher. Every other segment was numbered in sequence from 1 to 8. On the outer ring, the numbering started at the segment to the right of the bearing type number. On the inner ring, the numbering started to the right of the sequence number.

c. Each bearing was assembled and placed in a horizontal position in a glass container partially filled with Dalco DS-50 solvent and ultrasonically cleaned for five minutes. Each bearing was then removed and flushed with petroleum ether and allowed to air dry.

2. GREASING OF BEARINGS.

a. The selection of the grease was based on properties which were compatible with both the test conditions and the analysis techniques used by the NAVAIRENGCEN to separate the debris from the grease. The grease selected, Amoco Super MIL-Grease A72832, meets MIL-G-23827 specifications and consists of a lithium soap base and a diester lubricating fluid. The specified temperature range of the grease is -73°C to +120°C. Greases meeting this military specification are reportedly one of the three most frequently used greases in naval aircraft applications and is therefore representative of what would be found in practice.

b. Each bearing was charged according to standard practice with approximately 12.6 grams of Amoco Super MIL Grease A72832 to obtain a 1/3 full pack. The grease charge was inserted uniformly on both sides of the bearing between the balls using a hypodermic syringe. The grease was loaded into the syringe by inserting the large end directly into the grease supply and sucking the syringe full using a vacuum pump attached to the other end, thus avoiding the introduction of dirt and eliminating voids in the syringe pack.

c. The shields, cleaned with Dalco DS-50 solvent and petroleum ether, were then placed on both sides of the bearing and the bearing wrapped in coated paper in preparation for assembly into the test rig.

3. ASSEMBLY OF BEARINGS IN RIG.

a. Prior to the assembly of the bearings onto the shaft, the shaft bearing seats and surrounding area were washed with naphtha and wiped dry with a lint-free rag. The bearings were then pressed onto the shaft using the specially adapted hydraulic ram which was also cleaned with naphtha prior to use. The marked side of the bearing was located on the outboard side of the shaft.

b. The bearing housing, following cleaning with naphtha, was assembled with the bearing type number on the outer ring located at the 12 o'clock position.

c. The desired radial load of 2,600 pounds was then applied to each bearing. This was accomplished by calculating the necessary load to be applied to the load arm and checking the weights on a spring scale before attaching. The retaining bolts were then loosened to allow the load to be applied to the bearing.

d. The runout between the end of the shaft and face of the bearing housing was checked and the necessary adjustments performed to assure proper alignment before starting the test.

4. TESTING.

a. Bearing Set I was run in an uninterrupted manner. Testing was to be sustained until one of the following occurred: (a) a failure of both bearings was experienced, as indicated by an increase in bearing vibration level and/or audible noise, (b) a grease pack failure was experienced, as defined by the temperature rate of increase monitor, or (c) a bearing life of 230 million inner ring revolutions, roughly equivalent to the theoretical L_{50} , was achieved without failure. If testing was automatically stopped due to an excessive temperature increase rate or high temperature, the test was restarted and continued until stoppages occurred within 10 hours or less of each other.

(1) At the conclusion of the test, the bearings were carefully removed from the rig using a special puller which was cleaned with naphtha just prior to use. The major portion of the grease was then removed from the four areas (inner ring, outer ring, ball/cage, and shield) using a small, stainless-steel spatula and placed in separate compartments of a clean glass container. Each bearing was then placed in a glass container with Dalco DS-50 solvent and ultrasonically cleaned. Following the cleaning, the cleaning fluid and debris were placed in a glass bottle and sealed with a plastic cap using a teflon sealing disk. The grease and cleaning fluid were refrigerated until delivered to NAVAIRENGCEN personnel for analysis.

(2) The bearings were disassembled and a visual inspection of all elements performed using an optical microscope with magnification up to 30X. The inner ring surfaces were also examined with a scanning electron microscope to further determine the degree of surface damage and necessary photomicrographs were taken for documentation purposes.

b. Bearing Set II was tested in the same manner as Set I except grease samples were removed after 1, 5, 10, 20, 52, 80, 120, 160, and 230 million revolutions. The grease samples were removed from the outboard side using a small, stainless-steel spatula from a numbered segment on the cage, inner ring, outer ring, and shield starting with segment number 1 and progressing through number 8 after each progressive operating period. The removed grease was replaced by approximately the same quantity prior to re-starting the bearing. Following the test termination, the same procedure was followed in removing the grease and examining the bearing as in Set I.

c. Bearing Set III was tested in the same manner as Set II except at each shutdown interval, as specified in paragraph C above, the bearings were removed and the grease sampling, bearing cleaning, and examination performed in the same manner as that performed at the termination of Set I testing.

III. WEAR PARTICLE ANALYSIS

A. GENERAL

1. Wear particle analysis technology has been successfully applied as a nondestructive indicator of system surface wear condition in oil-lubricated equipment. This technology is based on the premise that debris generated during a wear process will reflect surface conditions present in the respective process. The generated debris, categorized by total quantity, size distribution, composition, and morphology (shape), can provide evidence as to system wear rate, wear severity, wearing components and active wear modes.

2. Unlike fluid-lubricated systems, in which the fluid and debris circulates through the entire unit, generated debris as well as any contaminants in grease-lubricated components are retained within the grease adjacent to the component. Therefore, for any given grease sample, the debris contained within is representative of that specific component and more precisely, from the actual segment of the component from which the sample was obtained. In terms of the four categories of debris mentioned above, morphology is the prime characteristic of debris for this evaluation. To a limited extent, the elemental composition and a gross estimation of size distribution and total quantity can be assessed.

3. Since the analytical equipment utilized in this study has been discussed adequately elsewhere (reference(c)), a brief statement of its operation is presented here. Figures 3 and 4 illustrate the subject equipment. The Ferrography method was utilized to assess the morphological characteristics of the retained wear debris. This technique employs a variable magnetic field to separate ferrous and hybrid wear debris from a prepared sample, and selectively arranges the particles according to size. This arrangement facilitates the determination of the morphological characteristics by microscopic examination.

B. SAMPLE PROCESSING. In order to conduct wear debris analysis of the grease samples, an effective method to dissolve the grease matrix first needed to be developed. The Ferrographic technique utilized required the grease be dissolved so as to result in a fluid-type mixture capable of being passed through a narrow tube (by means of a pump) onto a glass substrate. In addition to assuring a fluid-type composition, the resulting mixture would produce an acceptable ferrogram to analyze the resulting wear particulate. This would serve as an aid in trending the wear state condition of the component.

C. SOLVENT EVALUATION. In order to dissolve the grease, a study was undertaken to evaluate various solvent combinations (reference(d)). Due to the various additives used in the composition of greases, a single, universal solvent could not be found. Various unused greases were tested, using various amounts of grease and combinations of solvents, based upon solubility and

Ref: (c) Tessman, R. K., Fitch, E. C., "The Survivability Characteristics of Fluid Power Components in Contaminated Environments", Office of Naval Research, Annual Report on Contract No. N00014-75-C-1157 (1976).

(d) NAVAIRENGCEN Report NAEC-92-129 of April 1979: "Wear Particle Analysis of Grease Samples," prepared by Foxboro Company, under Contract No. N68335-76-C-2281.

residue of the resulting mixture. From these tests, three grease solvents were chosen upon their wide-spread application. Solvent 1 was composed of 50% toluol and 50% isopropanol. This solvent was found to be ineffective with lithium soap greases. Solvent 2 was composed of 33% toluol 33% methyl ethyl ketone and 34% isopropanol. This solvent showed a somewhat similar effect as Solvent 1 on lithium soap grease. Solvent 3, composed of 30% toluol and 70% hexane, appeared to be the most universal solvent, as its solvating action is applicable over a wide selection of greases, including lithium soap grease.

D. USED GREASE ANALYSIS. During testing of the various solvents, the grease being solvated was in an unused state as opposed to a "worked condition". These unused grease samples were found to contain various metallic and non-metallic particulates.

1. The metallic and nonmetallic particulates, contained in the unused grease, appear to be from the processing and packaging of the grease. Numerous studies were conducted in order to characterize this particulate. In addition, Scanning Electron Microscopy (SEM) and Energy Dispersive X-Ray Spectroscopy (XDS) analyses were conducted to determine shape and elemental composition. This work resulted in data which enabled the evaluator to discriminate between those particulates from the unused grease and those from the actual wearing component.

2. In order to determine the difference in solvating unused and worked grease, numerous used grease samples were obtained from aircraft components and subjected to the various solvents stated previously. As a result of these studies, Solvent 2 was found to be more effective with worked grease. The principle reason was the ferrograms were virtually free of residual grease material as opposed to that observed using Solvent 3. Therefore, Solvent 2 was chosen for use in the program.

E. TEST SAMPLING.

1. The grease samples from the bearing test were obtained from four different locations (inner ring, outer ring, ball/cage, and shield) each time samples were extracted. The quantity of grease removed was representative of the actual amount of grease present at the time of sampling. This served as an indicator as to what areas of the bearing furnished adequate amounts of grease for actual field sampling. These various sampling locations were studied to determine the sensitivity to the actual wear of the bearing surfaces by wear particle retention.

2. It was observed during the grease sampling that fretting material generated between the bearing housing and outer ring sometimes dropped into the grease on the bearing shields during the removal of the bearing from the shaft or during grease sample removal. Attempts were made to remove this material from all samples supplied to NAVAIRENGCEN to eliminate confusion

during evaluation. However, since there was no assurance that all fretting material was removed, a sample of the material was supplied to NAVAIRENGCEN for examination and categorizing, thus permitting its identification if found in the grease samples. Although the presence of the fretting material was undesirable, it was also quite likely that it would be present in some field applications and special care would have to be taken to minimize it in grease samples.

F. PREPARATION PROCEDURE. The procedure for preparation of the grease samples for Ferrographic analysis was accomplished in the following manner.

1. Ten 3mm-diameter glass beads were placed in a 1/2 ounce bottle. The use of these glass beads aided the agitation process of the grease solution. Their presence had no noticeable effect on the resulting ferrograms.

2. Varying amounts of used grease, ranging in size by weight of between 0.01 to 0.035 gm, were then added to the bottle. The amount used corresponded to the time of the sample extraction and the operating parameters of the specific test.

3. Five (5)cc of Solvent 2 were poured into the bottle. The sample bottle was then closed and hand shaken vigorously until such time that the grease became dispersed.

4. Five (5)cc of filtered MIL-C-23699, a synthetic ester-based fluid, was then added to the grease mixture. This fluid was added to increase the viscosity index of the grease mixture to aid in the delivery of the mixture to the ferrogram substrate. Additionally, the grease used (MIL-G-23827) has a diester lubricant additive, which makes it compatible with MIL-C-23699.

5. The sample was then recapped and shaken vigorously. Five (5)cc of the grease mixture/ester solution was then removed by pipet into another 1/2 ounce bottle. A ferrogram was then prepared from this mixture using filtered Solvent 2 as a washing/fixing solution.

Utilizing these ferrograms, a microscopic examination of the wear debris was performed in order to assess the wear state/condition of the bearing element.

IV. TEST DISCUSSION AND RESULTS

A. DISCUSSION

1. Of the six bearings tested, three experienced failures which terminated their testing before time-up and a fourth experienced several TRIM shutoffs before reaching time-up. Of the three failures, two were the results of inner-ring spalls and the third due to TRIM shutoffs which occurred within three hours of each other (bearing 02).

2. The decision to continue testing after a TRIM shutoff was based on the belief that the intermittent stopping would be more representative of that experienced in an aircraft application. Thus, the accumulation of debris trapped in the grease from bearing 02 would also be more representative of that expected in an actual field application before a bearing failure.

3. The test portion of the program was considered to be quite successful since typical spall failures and inadequate lubrication failures both occurred and two bearings reached test time-up without failing; thus providing a well-distributed cross section of occurrences without any catastrophic failures.

4. Wear particle analysis was performed on the resulting used grease samples by the NAVAIRENGCEN. The information obtained from these analyses were subjected to a trend analysis and a determination of the surface/lubricant condition was discerned. Throughout the entire test portion of the program, information and test data were not exchanged between SKF and NAVAIRENGCEN in order to avoid influencing the analysis of the wear debris evaluator.

5. For ball bearings in general, the type of ferrous particles normally associated with wear, in order of frequency are:

- a. Benign rubbing wear particles
- b. Laminar particles
- c. Break-in or wear-in particles
- d. Severe wear particles
- e. Fatigue particles
- f. Abrasive particles
- g. Spherical particles

A more in-depth coverage, including numerous photomicrographs, of these and other types of wear debris is to be found in the NAVAIRENGCEN Wear Particle Atlas (reference (e)).

6. Briefly stated, during a typical wear-in or start-up of a bearing, miscellaneous ribbon-shaped particles are generated, in addition to benign rubbing wear particles. Transitioning to a normal wear period or operation, the rubbing wear particles dominate in number, with trace amounts of laminar, abrasive, and fatigue wear particles. As an abnormal wear situation develops, the predominant wear particle types that could appear are laminar, severe and fatigue wear, along with lesser amounts of abrasive, rubbing, and spherical wear debris.

7. In addition to the morphology of the wear debris, other data available from the analysis was the gross estimation of the ratio of large to small (L/S) particles and an assessment of the wear severity for each bearing. The ratio of L/S particles is the gross estimation (quantity) of large particles (5 microns and above) to the number of small particles (below 5 microns) of the same material type. This estimation is accomplished by viewing the ferrogram slide with an eyepiece micrometer disc, utilizing the initial 7-10 mm of the ferrogram deposit, starting with the entry point. For ball bearings, in general, the range for the wear-in or break-in period is between 1:50 to 1:150; normal wear, 1:150 to 1:500; and wear-out or failure, 1:150 and under (reference (f)).

Ref: (e) NAVAIRENGCEN Report of July 1976: "Wear Particle Atlas," prepared by Foxboro/Transonics, Incorporated, under contract No. N001-56-74-C-1682.

(f) Bowen, E. R., Senholzi, P. B., "Oil Analysis Research," National Conference on Fluid Power (1976).

8. The wear severity is a function of the generation rate and distribution of the wear debris. This assessment is based upon the results obtained from the density reader, a photo diode device installed in the optical path of the microscope. Typically, readings are obtained at two specific points on the ferrogram (entry deposit and 50mm) representing the large and small ferrous metallic debris respectfully. In general, the higher the numerical value, (157,000 versus 6,000) the greater the quantity of large particles (greater than 5 μ m) as well as the total quantity of all particles generated. In a conventional system, higher values of wear severity are observed during the wear-in and wear-out phases, with a fairly constant value during normal wear operation. The use of the wear severity in research applications such as this can aid in determining relative ranges of wear regimes in order to facilitate a continuous monitoring effort. The number/values generated in this method are for comparison purposes, specifically within this test. Comparisons are then drawn upon the relative difference between values for each bearing/sample.

9. The testing record of each bearing is presented in Appendix A and the optical microscope examination observations are presented in Appendix B.

B. TESTING RESULTS

1. SET I BEARINGS (BEARINGS 01 AND 02). The testing of Set I bearings progressed uneventfully for a period of 158 hours, when a temperature rate of increase monitor (TRIM) shutoff occurred due to a fast rise in bearing 02 temperature. After a down-time of seven hours, giving the oil time to bleed into the bearing, the machine was restarted and operation continued. After four additional TRIM shut-offs, with only three hours of operation between the last two, and one high-temperature shut-off, the testing of bearing 02 was terminated after 302 hours or 98×10^6 revolutions. The grease was removed and the bearing cleaned and inspected. Testing of bearing 01 was continued using a dummy bearing in place of 02. After an additional operation of 5×10^6 revolutions or a total of 103×10^6 revolutions, a TRIM shutoff occurred. After attempting to restart the test, a vibraswitch shutoff occurred, indicating that a spall had occurred.

a. Bearing 01 Analysis

(1) Surface Analysis (Bearing 01).

(a) A post-test photomicrograph of the inner ring of bearing 01 is presented in Figure 5. This photograph shows that the ball track is quite similar to that in bearing 02 with banding quite prominent. A spall is also shown along with the numbered areas of which photomicrographs at 500X were also taken.

(b) The photomicrographs of the various areas are presented in Figure 6. These photographs show that appreciable surface distress had occurred which consisted of appreciable micropitting, denting, and plastic deformation. The surface damage in this bearing was not as severe as in bearing

02. The test history would suggest that less surface damage should have occurred since the test was terminated after only one TRIM shutoff due to the simultaneous spall failure. A 50X magnification of the spall is presented in Figure 7 which shows that one piece approximately 0.5 x 0.5 mm had flaked from the surface and many surface cracks had developed. To permit a comparison of the damaged surface with an original surface, a 500X photograph is presented in Figure 8 which shows a "fresh" ground surface of the race.

(c) The surface damage and the initiation of a spall that occurred in this bearing would dictate its replacement as further running would quickly result in an inoperative bearing.

(2) Wear Debris Analysis

(a) Due to the nature of the test design, only one set of samples was obtained, those being at the time of failure. Ferrograms were made of the resulting samples to determine the best location for sampling in terms of the amount of grease available and the representatives of the wear debris to the actual wear condition.

1. Inner Ring. An insufficient amount of grease on the inner ring prevented the preparation and analysis of the wear debris.

2. Ball/Cage Sample. Microscopic examination revealed a significant amount of abnormal wear particles (see Figure 9). Of the total amount of wear particle types observed, 30% were rubbing wear, 55% laminar, 8% severe, and 7% fatigue. The percentage of rubbing wear particles was low, indicating that these particles had somehow been displaced; however, there exists no explanation for this occurrence. Since the grease in the bearing was never removed or replenished, the wear particles from start-up to failure should have been cumulative to some extent. Temper coloration (surface oxidation, associated with high temperature exposure) was observed on a number of the particles. The particles in general seemed to exhibit a high major dimension to thickness ratio. Measurement of the wear severity indicated an extremely high wear debris generation rate (157,000) reflecting an abnormal wear condition. The ratio of large-to-small particles (1:143) indicated a somewhat high generation rate of large particles in proportion to small particles.

3. Outer Ring Sample. Microscopic examination revealed a moderate amount of abnormal wear particles, with 40% rubbing wear, 50% laminar, 5% fatigue and 4% severe wear. High amounts of laminar and lesser amounts of fatigue wear particles were observed. Some temper coloration was observed. The wear severity measurement indicated a mild wear rate (12,000), considerably less than the cage and ball. The ratio of large-to-small particles (1:150) revealed a somewhat high amount of large particle generation.

4. Shield Samples. For this sample, the wear severity is extremely low (1,200) in comparison with the cage and ball and outer ring samples. The high ratio of large-to-small particles (1:131) is representative of an abnormal amount of large wear debris particles. Since the shield is not an actual operating segment of the bearing, the wear debris contained within

this grease sample are the result of migration from the working areas of the bearing. The presence of predominantly large particles in this sample suggests the need for a closer examination of the trend of particle migration outward from the interior of the bearing.

(b) Based upon the results of these ferrograms, the ball/cage sampling location best reflected the actual wear state of the bearing as well as provided an adequate amount of grease for testing. The inner ring had an insignificant amount of grease, therefore it was not pursued. The outer ring provided an adequate amount of grease for analysis, yet the size distribution and total number of particles were considerably less than the ball/cage sample. The shield contained an adequate amount of grease, but the size distribution and total number of particles were considerably greater than either the ball/cage and outer ring. Since the shield was not an actual wearing component of the bearing, the particles in these grease samples could not be precisely identified as to their origin. Therefore, for the purpose of this study, the major emphasis was placed on the ball/cage sample only.

b. Bearing 02 Analysis.

(1) Surface Analysis.

(a) A photomicrograph of the inner ring of bearing 02 following test termination is presented in Figure 10. This photograph shows the top view of an inner race segment at 4X magnification and on either side of the race a portion of each land which appears bright or shiny. In the center of the race, the ball track which extends over approximately 1/3 of the race width is quite obvious due to the change in the surface finish that had occurred. Five bands can easily be detected with the outside edges of the outer bands dark in appearance. These bands are the result of the relative kinetics between the ball and the race.

(b) In a radially loaded bearing, there is pure rolling at only two points in the contact area. In the remaining contact areas there is a tendency for microslip to occur. This condition results because the length of the radius from the axis of rotation of the element varies with position on the ball surface. The two bands produced on the races at the points of pure rolling are referred to specifically as the Heathcote bands. The slip between the Heathcote bands where the load is the greatest is negative or opposite to the direction of rolling. The slip external to the Heathcote bands where the load decreases to zero as you move outward is positive.

(c) Scanning electron microscope (SEM) photomicrographs of areas within the five bands are presented in Figure 11. Figure 11A, of the center slip band, shows a highly glazed area with a few micropits, dents, and one microspall. Figures 11B and 11C are photographs of the Heathcote bands and show appreciable micropitting due to pulling or material removal which results from the welding together of asperities during metal-to-metal contact under high pressure. Figures 11D and 11E are photographs of the outer slip bands which also show many micropits and dents and some microspalls. The plastic flow and wear in these bands are less than in the other three bands as evidenced by the presence of some of the finish grinding lines. Figures 11F and 11G are photographs of the outer edges of the outer slip bands and show areas where little plastic flow and wear had occurred and approaches virgin surface.

(d) In general, the inspection shows that this bearing had appreciable surface distress which indicates that inadequate lubrication had existed at some time during its operation. This result agrees well with the test history presented in Table A2 (Appendix A) which shows that the testing was stopped four times due to TRIM and once due to high temperature. Both types of stoppages are indicative of inadequate lubrication.

(e) Although the damage to this bearing is not sufficient to prevent further operation if it were regreased, the period of further operation before a surface-initiated spall is likely to occur is considered to be greatly reduced when compared to an undamaged bearing. Should the bearing be continued in use without regreasing, a thermal imbalance failure is likely to occur within the next few hours of operation. Thus a bearing in this condition should be replaced.

(2) Wear Particle Analysis

(a) Inner Ring Sample. An insufficient amount of grease prevented the preparation and analysis of the wear debris.

(b) Ball/Cage Sample. A high amount of abnormal wear particles was observed (see Figure 2). Of the total amount of particle types observed, 40% were rubbing wear, 40% laminar, 16% severe wear, and 4% fatigue. The percentage of rubbing wear was low, as with bearing 01. Temper coloration was observed quite readily on a significant number of large particles. Some particles appeared to be partially oxidized, while others appeared to be ground up, much like a piece of crushed aluminum foil. The wear severity revealed an extremely high debris generation rate (175,000), indicating an abnormal wear state. The ratio of large-to-small particles was 1:156, reflecting an unstable generation of large wear debris.

(c) Outer Ring Sample. Microscopic examination revealed a large amount of laminar and abrasive wear, with a low percentage of rubbing wear (30%). The wear severity (7,000) was considerably lower than the ball/cage sample. Temper coloration was again noted on a large number of particles. The ratio of large-to-small (1:140) suggests the migration of large particles, as was observed in bearing 01.

(d) Shield Sample. The large particles were disproportionate in number as reflected in the ratio of large-to-small particles (1:140). In addition to particles normally viewed, fretting wear, presumed to be from the bearing housing, was observed and noted.

2. SET II BEARINGS (BEARINGS 03 AND 04). The testing of Set II bearings 03 and 04 proceeded without incident, with grease samples removed as scheduled after 1, 5, 10, 20, 52, 80, 120, 160, 225, and 231 million revolutions. During the testing period from 160 million revolutions until test time up of 231 million revolutions, four TRIM shutoffs occurred due to excessive temperature increase rates in bearing 04 with no shutoffs occurring due to problems in bearing 03. The post-test examination of the two bearings in this set readily depicts the differences in the surface condition of two bearings operating for equal periods under identical loads, with one bearing experiencing inadequate lubrication during a portion of its operation.

a. Bearing 03 Analysis(1) Surface Analysis.

(a) The photomicrograph of bearing 03 in Figure 13 shows the excellent condition of the inner race surface following test termination. Close inspection of this photograph shows the presence of finish grinding lines across the complete race width including the ball track area. Also obvious is the lack of detectable banding. These two conditions indicate that minimal wear and plastic flow had occurred and that the bearing was well lubricated throughout the test.

(b) Figure 14 presents several photomicrographs of the major defects observed in the SEM examination of bearing 03. Figure 14A shows a gouge in the surface probably caused by a hard piece of debris forced across the surface which actually machined the material out. Figures 14B and 14C show multi-fragment dents which resulted from fragmented pieces of debris pressed into the surface. Figure 14D shows two dents, each produced by single pieces of debris. The presence of the finish grinding lines in the bottom of the dents readily distinguish them from pits or spalls. The finish grinding lines outside of the dented areas corroborate the conclusion that little wear and plastic flow had occurred in this bearing. The surface of bearing 03 was in excellent condition and would probably run for many more hours without a failure, barring a classical fatigue failure which is unpredictable.

(2) Wear Particle Analysis. In addition to results of the various sample locations, the remainder of the wear particle analysis will be presented in three distinct phases of life-wear-in, normal wear, and wear-out. The determination of these phases is based upon the microscopic examination of the wear debris.

(a) Wear-In.

1. The wear-in period for bearing 03 was evident in the 1- and 5-million revolution samples (see Figure 15A). The percentages of particle types for this period are presented in Table 1.

TABLE 1

WEAR PARTICLE TYPE/FREQUENCY IN BEARING 03
BALL/CAGE SAMPLE DURING WEAR-IN PERIOD

SAMPLE PERIOD	TYPE WEAR PARTICLE (%)			
	RUBBING	FATIGUE	LAMINAR	SEVERE
1 Mil Rev	65	2	10	20
5 Mil Rev	75	1	10	3

Wear-in particles (long, narrow metallic strips), normally associated with the break-in of new surfaces, were observed in considerable quantities. The wear severity (6,000) and ratio of large-to-small particles (1:180) indicate that a normal wear-in of the surfaces was occurring.

2. The outer ring and shield samples observed generally agree with the observations made of the ball/cage sample.

(b) Normal Wear.

1. At the 10-million-revolution sample point, microscopic examination of the wear debris indicated that the bearing wear had stabilized. Further examination of the samples obtained at 20, 52, 80, 120, and 160 million revolutions revealed a continuance of the normal wear of the bearing. The percentage of particle types for this period are presented in Table 2.

TABLE 2

WEAR PARTICLE TYPE/FREQUENCY IN BEARING 03
BALL/CAGE SAMPLE DURING NORMAL-WEAR PERIOD

SAMPLE PERIOD	TYPE WEAR PARTICLE (%)			
	RUBBING	FATIGUE	LAMINAR	SEVERE
10 Mil Rev	60	1	25	12
160 Mil Rev	30	5	55	10

Throughout the period, the normal wear particles were the dominant type, with a marked increase occurring in the 20-million-revolution sample. Between the 120- and 160-million-revolution sample points, the percentage of rubbing or normal wear particles decreased dramatically, while at the same time, there was a substantial increase in laminar particles. Other particle types also experienced a gradual increase in number (see Figure 15B). The wear severity (16,000) and ratio of large-to-small particles (1:194) at 160 million revolutions, suggest that the generation rate of the particles was normal, with a slight, upward trend in the wear severity.

2. Examination of the outer ring and shield samples both indicated a normal-wear period between 10 and 160 million revolutions.

(c) Wear Out.

1. An unstable wear state initiated between the 160- and 231-million-revolution sample points. At the termination of the test (230 million revolutions), this unstable condition had not reached a critical point or failure initiation. Particle makeup for this period is illustrated in Table 3.

TABLE 3

WEAR PARTICLE TYPE/FREQUENCY IN BEARING 03
BALL/CAGE SAMPLE DURING WEAR-OUT PERIOD

SAMPLE PERIOD	TYPE WEAR PARTICLE (%)			
	RUBBING	FATIGUE	LAMINAR	SEVERE
160 Mil Rev	30	5	55	10
231 Mil Rev	25	5	40	20

Examination of the 231-million-revolution sample revealed only an increase in the amount of severe wear, with a corresponding decrease in laminar particles (see Figures 15C and 15D). Wear severity measurement was not possible due to nonmetallic debris in the critical measuring areas. The ratio of large-to-small particles (1:180) indicated that a relatively stable generation rate of particles was occurring. Figure 16 illustrates the trend data of large-to-small particle ratio for bearing 03 for the respective sample locations.

2. Outer-ring and shield samples were in concurrence with the exception of abrasive wear observed in the outer-ring sample at 231-million-revolutions. The origin of the abrasive wear particle could not readily be determined.

b. Bearing 04 Analysis

(1) Surface Analysis. In contrast to bearing 03, bearing 04 had appreciable surface distress and was very similar to bearings 01 and 02. A photomicrograph of the inner race, Figure 17, shows the banding that had occurred and the glazed surface in the center of the track. Photomicrographs of the center slip band and the two outer slip bands are presented in Figure 18. Figure 18 shows the high degree of glazing and three microspalls, probably surface initiated, that had occurred in the center slip band. Also shown are the micropitting, denting, and plastic flow that had occurred over the major portion of the ball track. The initiation of a spall in the center band is shown in view D of Figure 18.

(2) Wear Particle Analysis.

(a) Wear-In.

1. The wear-in period for bearing 04 was evident in the 1-, 5-, and 10-million-revolution samples. This was approximately 5 million revolutions longer than bearing 03. Noticeably absent was the presence of the wear-in type particles previously commented upon in bearing 03 samples. Microscopic evaluation of the wear particle types indicate a severe wear-in process had occurred (see Figure 19A). The percentage of particles for the wear-in period is presented in Table 4.

TABLE 4

WEAR PARTICLE TYPE/FREQUENCY IN BEARING 04
BALL/CAGE SAMPLE DURING WEAR-IN PERIOD

SAMPLE PERIOD	TYPE WEAR PARTICLE (%)			
	RUBBING	FATIGUE	LAMINAR	SEVERE
1 Mil Rev	25	0	5	6
10 Mil Rev	65	0	20	10

The wear severity (46,000) was considerably high, indicative of a severe wear-in process. The ratio of large-to-small (L/S) particles (1:225) suggests a moderate generation rate at 10 million revolutions; however, the L/S ratio for the first two samples (1:115) and (1:120), respectfully, indicated a great amount of large particles being generated.

2. Examination of the outer ring and shield samples revealed an abnormal wear-in, both possessing high ratios of large-to-small particles.

(b) Normal Wear.

1. After the 10-million-revolution sample, a normal wear mode had occurred and continued to the 120-million sampling point, where evidence of unstable wear was noted. Particle makeup for the period is listed in Table 5.

TABLE 5

WEAR PARTICLE TYPE/FREQUENCY IN BEARING 04
BALL/CAGE SAMPLE DURING NORMAL-WEAR PERIOD

SAMPLE PERIOD	TYPE WEAR PARTICLE (%)			
	RUBBING	FAILURE	LAMINAR	SEVERE
10 Mil Rev	60	1	35	5
120 Mil Rev	30	1	55	3

2. Throughout this period, noticable increases in the number and size of particles were observed as the time of the test increased. In particular, there was a dramatic increase in the number of all particle types in the 20-million-revolution sample (see Figure 19B). The wear severity, calculated for the 10- and 20-million revolution samples, showed more than a threefold increase, 46,000 to 133,000, respectfully.

3. The wear-in type particles, noticably absent during the first two samples, began to appear in the 10-million-revolution sample. For this sample, the ratio of large-to-small samples was 1:220, indicating that the severe operating condition noted in the first samples had subsided.

4. The outer ring and shield samples again generally coincided with the above analysis, except for the presence of numerous abrasive wear particles observed in the outer ring samples.

(c) Wear Out.

1. An unstable wear rate was evident, beginning with the 160-million revolution sample. This unstable condition appeared approximately 40 million revolutions earlier, compared to the samples of bearing 03. At the termination point of the test run (231 million revolutions), the grease had degraded to such an extent, as to prohibit any close analysis of the wear debris (see Figures 19C and 19D). Grease degradation by-products (gel-like substance) completely covered or entrapped a majority of the particles, limiting the morphological aspect determination and negating any quantitative data. The data illustrated in Figure 20 is subjective after the 160-million-revolution point, due to the degradation of the grease.

2. A similar degradation process was experienced in the outer ring and shield samples.

3. SET III BEARINGS (BEARINGS 05 AND 06). The testing of Set III bearings 05 and 06 proceeded without incident, with all the grease removed, bearings cleaned, examined, and regreased as scheduled after 1, 5, 10, and 20 million revolutions. At 52 million revolutions, a vibraswitch shutoff due to a spall failure on the inner race of 06 occurred. Bearing 06 was replaced with a non-test bearing and testing continued with bearing 05. The grease in 05 was removed and the bearing inspected at 80, 120, 160, and test time-up of 230 million revolutions without any unscheduled shutdowns.

a. Bearing 05 Analysis.

(1) Surface Analysis.

(a) A photomacrograph of the inner ring of bearing 05 taken after 2 million revolutions is presented in Figure 21. This photograph shows the finish grinding lines across the complete race which indicates that little wear and plastic flow had occurred. Also shown are the grinding furrows which were observed after 1 million revolutions. These furrows extend around the complete circumference and had no doubt occurred during the manufacturing process. No changes were produced in these furrows during the testing.

(b) Photomicrographs of the major damaged area are shown in Figure 22, with the azimuth locations noted. In all three areas, one or more multi-fragment dents had occurred and the finish grinding lines were still present. Photomicrographs taken after 230 million revolutions (test time-up) of these same areas are presented in Figure 23 and show that no appreciable change had occurred at the damaged areas, except for an appreciable increase in micropitting. The micropitting indicates that the quality of the lubrication had worsened at some point during the extended running. Although this bearing was in relatively good condition, its replacement would be recommended.

(2) Wear Particle Analysis.(a) Wear-In.

1. The microscopic examination of the wear particles indicated that the break-in or wear-in occurred up to the 10-million-revolution sample point. Particle makeup for this period is found in Table 6.

TABLE 6

WEAR PARTICLE TYPE/FREQUENCY IN BEARING 05
BALL/CAGE SAMPLE DURING WEAR-IN PERIOD

SAMPLE PERIOD	TYPE WEAR PARTICLE (%)			
	RUBBING	FATIGUE	LAMINAR	SEVERE
1 Mil Rev	60	10	20	10
10 Mil Rev	40	5	40	5

2. A large quantity of particles was observed. Wear-in type particles were observed in the 1-, 5-, and 10-million-revolution samples (see Figure 24). The quantity of rubbing wear particles was not as high as in the previous bearing samples analyzed at this point in time of the test. The ratio of large-to-small particles remained slightly higher than would normally be observed (1:125 for all three samples). Figure 25 illustrates the trend in large-to-small data for bearing 05. The wear severity had an initial high value in the 1-million-revolution sample (26,000) but dropped to 2,000 in the 10-million-revolution sample. The rubbing-, laminar-, and severe-wear-type particles were larger in size than had been observed in previous samples (see Figure 26A). Due to the test nature (dismantle and inspection) a large portion of the quantitative data is negated.

3. The outer ring and shield samples showed a less pronounced amount of large particles and their frequency. This may be attributed to the nature of the test (long versus short period of running times) which would explain the decline in the number of wear particles retained in the grease and the resulting effect of the migration process previously cited.

(b) Normal Wear.

1. A transition to normal wear occurred after the 10-million revolution sample point and continued on to the 120-million-revolution sampling point as evidenced by the morphology and frequency of the observed particles. The particle makeup is illustrated in Table 7.

TABLE 7

WEAR PARTICLE TYPE/FREQUENCY IN BEARING 05
BALL/CAGE SAMPLE DURING NORMAL-WEAR PERIOD

SAMPLE PERIOD	TYPE WEAR PARTICLE (%)			
	RUBBING	FATIGUE	LAMINAR	SEVERE
20 Mil Rev	40	5	40	8
120 Mil Rev	30	2	53	5

Throughout this period, normal wear progressed, marked by stepped increases at the 52- and 80-million revolution sample points. Of particular note was the continued presence of wear-in type particles. This may be the result of the dismantling and reassembling of the bearing at each sample point. The wear severity increased markedly from the 52- to the 80-million-revolution samples, indicating an increase in the rate of wear particle generation, although the particle sizes stayed approximately the same (see Figures 26B and 26C). A large quantity of abrasive wear was noted in the 80 million revolution sample.

2. The outer ring and shield samples remained about the same throughout this period, with the exception of some temper coloration noted.

(c) Wear Out.

1. Starting with the 120-million-revolution sample, an unstable wear condition was observed. The condition of the grease had begun to degrade slightly, causing some problems in obtaining accurate particle analysis. However, at the termination point, the wear analysis of the particles indicated that there appeared to be no appreciable surface degradation of the bearing (see Figures 26D and 26E). Particle ranges for this final period are presented in Table 8.

TABLE 8

WEAR PARTICLE TYPE/FREQUENCY IN BEARING 05
BALL/CAGE SAMPLE DURING WEAR-OUT PERIOD

SAMPLE PERIOD	TYPE WEAR PARTICLE (%)			
	RUBBING	FATIGUE	LAMINAR	SEVERE
120 Mil Rev	30	2	53	5
230 Mil Rev	25	3	60	8

An interesting note was that the grease appeared to degrade in bearing 05 as in bearing 04; however, the grease was completely changed after each inspection as opposed to only minute samples removed and replaced in bearing 04.

2. The outer ring and the shield samples were somewhat affected by the degradation of the grease, but on a lesser scale.

b. Bearing 06 Analysis.

(1) Surface Analysis.

(a) A photomicrograph of the inner race of bearing 06 after 20 million revolutions is presented in Figure 27. This photograph shows only minor denting and the presence of the finish grinding lines across the complete race, which indicates that little wear and normal plastic flow of asperities had occurred. Photomicrographs of the major damaged areas are shown in Figure 28 with the azimuth angles noted. In all four areas, a multi-fragment dent had occurred. These photographs also show the presence of the finish grinding lines.

(b) Figure 29 is a photomicrograph of the inner ring of bearing 06 after 52 million revolutions. This photograph shows that little additional wear had occurred, but an appreciable increase in the denting had resulted. This denting is considered to have resulted from debris produced by the spall failure shown in Figure 30 which occurred at an azimuth location of 140°. No surface damage was noted at this location after 20 million revolutions; therefore, it must be considered to be a classical fatigue spall and not a surface-initiated spall. Figure 31 presents photomicrographs of the damaged areas previously presented. These photographs indicate that no observable changes had occurred in the dents and the finish grinding lines were still prevalent.

(2) Wear Particle Analysis.

(a) Wear In. The wear-in period for bearing 06 was evident in the 1- and 5-, and 10-million-revolution samples. A large number of metallic wear debris particles were observed (see Figure 32). In addition, several large metallic and nonmetallic particles were observed (see Figure 33), the origin of which could not be identified. A possible source of these particles was from the grease as received. There was a noticeable absence of the typical break-in type particles in all three samples during this period. The numbers and size of the rubbing wear was normal; however, the number of laminar wear particles was high in terms of the test time. The ratio of large-to-small particles (1:200) was slightly below normal. The wear severity (50,000) was extremely high in relation to the other bearings at this point in the test. Table 9 illustrates the particle makeup during this period.

TABLE 9

WEAR PARTICLE TYPE/FREQUENCY IN BEARING 06
BALL/CAGE SAMPLE DURING WEAR-IN PERIOD

SAMPLE PERIOD	TYPE WEAR PARTICLE (%)			
	RUBBING	FATIGUE	LAMINAR	SEVERE
1 Mil Rev	75	0	12	6
5 Mil Rev	79	0	20	0

(b) Normal Wear.

1. A transition to normal wear was observed in the 10- and 20-million-revolution samples. The particle makeup for this period are listed in Table 10.

TABLE 10

WEAR PARTICLE TYPE/FREQUENCY IN BEARING 06
BALL/CAGE SAMPLE DURING NORMAL-WEAR PERIOD

SAMPLE PERIOD	TYPE WEAR PARTICLE (%)			
	RUBBING	FATIGUE	LAMINAR	SEVERE
10 Mil Rev	47	0	44	5
20 Mil Rev	17	0	75	8

A dramatic increase in laminar particles was observed in the 20-million-revolution sample, with a corresponding decrease in rubbing wear. Particles associated with wear-in or break-in, absent during the initial period of testing, were still not observed. In spite of the large increase in laminar particles, the overall number of particles decreased to a normal level, with the ratio of large-to-small particles (1:208) and wear severity (3,200) reflecting this decline. However, the wear severity, although not extremely high, did increase by a factor of 2 over the previous sample.

2. The outer ring and shield samples showed signs of normal wear in the 10-million-revolution samples; however, the number of abnormal wear particles in the 20-million-revolution samples increased noticeably.

(c) Wear-Out.

1. An unstable wear condition was observed in the 52-million-revolution sample. This sample exhibited an extreme increase in the number, type, and size of particles (see Figure 34). The particle types and frequency are listed in Table 11.

TABLE 11

WEAR PARTICLE TYPE/FREQUENCY IN BEARING 06
BALL/CAGE SAMPLE DURING WEAR-OUT PERIOD

SAMPLE PERIOD	TYPE WEAR PARTICLE (%)			
	RUBBING	FATIGUE	LAMINAR	SEVERE
52 Mil Rev	20	7	0	10

The wear severity (17,000) and the ratio of large-to-small particles (1:160) were both very high in number, compared to the values for the same sample period in bearing 05. The size and amount of abnormal wear particles (especially fatigue and severe wear particles) was readily observable (see Figure 35). Temper coloration was observed in several of the larger particles, indicating a high temperature condition in the bearing. This information indicated that the bearing was wearing at an abnormal pace.

2. The outer ring and shield samples also showed signs of abnormal wear, with extremely large particles observed in both samples. Figure 36 illustrates the trend for bearing 06 in terms of the ratio of large-to-small particles.

V. OBSERVATIONS

1. The unused grease utilized in this study (MIL-G-23827A), was found to have contained a number of metallic and nonmetallic contaminants. In tests conducted in the NAVAIRENGCEN laboratory, samples of the unused grease, extracted from a previously unopened can, were tested. The samples were taken from various locations in the can. The resulting analysis revealed varying amounts of contaminant, in some cases, exceeding the limits set forth in the Military Specification for this grease.

2. The primary microscopic technique utilized in the analysis was the bichromatic-illumination method. The use of green transmitted light and red reflected light enabled the analyst to effectively observe the wear particulates in spite of the presence of translucent grease related substances, which at times, either entrapped or covered wear particulates.

3. As a result of the sample analysis, the ball/cage area was the best sampling location, followed by the outer ring and shield in that order. Peculiar was the migration of particles, particularly the larger (10 micron and above) ones, which seem to find their way to the shield area in greater numbers than the smaller ones.

4. The three test and sampling sequences utilized in this study had a marked effect on the quantity of particles, size ranges, and rate of generation of particles. In Set I (bearings 01 and 02), the test was run without interruption until failure or termination. The total number of particles was highest for this test. In Set II (bearings 03 and 04) the periodic sampling at different locations yielded lower large to small particle ratios and somewhat lower wear severity. Set III (bearings 05 and 06) had a significantly lower wear severity throughout the life and lower ratio of large-to-small particles as opposed to Set II. This is attributed to the nature of the test (dismantling and regreasing after each stoppage).

5. The effect of periodic dismantling and regreasing in Set III had a marked effect on wear condition. More specifically, restart after reassembly produced a quantity of wear particles, normally associated with a wear-in condition.

6. Bearings exhibiting a severe "wear-in" exhibited failures prior to reaching the L_{50} life. As a possible future endeavor, it would be interesting to investigate whether the severe "wear in" caused the failure or merely reflected a built-in abnormal situation.

7. The portion of grease removed from the sampling site during the test was representative of the amount of grease present at the time of sampling. This extracted material was further decreased when utilized in the wear debris analysis. The maximum amount of grease used for analysis by weight was 0.150 gram, with a minimum of 0.010 gram. Therefore, the stated ratios of large-to-small particles as well as wear severity are to be considered semi-qualitative at best.

8. Grease degradation by-products could not be totally eliminated from the analysis process. These by-products tended to complicate the analysis; however, their mere presence reflected an abnormal wear situation (see Figures 37 and 38).

9. Based upon the initial analysis of the generated ferrograms, the ball/cage sampling location best reflects the actual wear state of the bearing. This determination was made in light of the quantity and size distribution of the wear debris present as well as a sufficient quantity of grease available for sampling.

10. In order to solvate the used grease for analysis purposes, Solvent #2 (33% Toluol, 33% Methyl Ethyl Ketone and 34% Isopropanol) was utilized in order to produce the most effective ferrograms.

11. Based upon the observed morphological characteristics of the generated wear debris, the wear-in process for grease lubricated ball bearings appears to be similar to oil lubricated ball bearings. In addition to the morphological properties, the quantity and size distribution of particles is also similar.

12. The observed wear-in process, based on wear debris analysis, lasted generally up to the 10 million revolution point in the test. For those bearings which experienced severe wear-in or prolonged wear-in, they tended to fail earlier than their calculated L_{10} life.

13. The periodic dismantling and reassembling of the bearings in Set III (Bearings 05 and 06) had caused a wear-in process after each occurrence. This was noted primarily in the examination of the wear debris, in which the presence of the wear-in particles were observed.

VI. CONCLUSIONS

1. The bearing testing portion of this program was very successful since spall failures and inadequate lubrication failures both occurred and two bearings reached time up without indicating failure. The testing, therefore, provided a good distribution of failed and unfailed bearings from which the possible evaluation of bearing failure or imminent failure detection by wear debris analysis could be established, considering the limited sample size.

2. Wear particle analysis has been shown to be useful in evaluating the wear/state condition of grease lubricated components. The major achievement was the successful application of dissolving the grease utilizing a solvent mixture and making ferrograms of equal quality as to that found in oil analysis. The types of wear particles found in used grease samples are comparative to those found in oil lubricated systems.

3. The nature of a grease lubricant creates several problems with respect to the monitoring of the four critical wear particle parameters. The main difficulty is that a simple measurement of the wear metal concentration in a grease sample does not necessarily reflect the present wear condition of the lubricated component. There are at least two reasons for this situation. First, the products of wear are not distributed uniformly in the grease. Hence, a grease sample will not necessarily reflect the total wear product concentration. Second, the products of wear do not leave the component through the lubricant and consequently the wear particle concentration will increase with time. Thus, the equilibrium concentration of wear debris, characteristic of oil-lubricated systems, does not apply in grease-lubricated systems.

4. The analysis of the grease samples was qualitative vs quantitative; due to the uneven distribution of wear particulate in the grease and the relatively small amount of grease used in making the ferrograms. The primary emphasis was placed upon size distribution, morphology, and elemental composition of the generated wear particulate.

5. The results of the ferrogram analysis showed a good correlation to those of the SKF personnel in terms of monitoring the wear state/condition of the bearings throughout their life. However, the on-condition monitoring of grease lubricated components in the field, is complicated by the physical location of the components and inaccessibility by maintenance personnel to remove grease samples. Where accessibility is no problem, this technique is highly recommended. As it appears presently, this analysis technique seems best suited to the examination of grease obtained from dismantled grease lubricated components or in design applications.

VII. RECOMMENDATIONS

1. The next logical step in the development of the wear debris analysis for predicting imminent failure in grease lubricated ball bearings is the application of the preliminary results to judge the conditions of additional bearings run in a laboratory environment. This continued activity is required to establish the overall reliability of this failure prediction technique while obtaining additional experimental data under controlled conditions and allowing for further improvement of the procedures. To reliably accomplish these objectives, it is suggested that a minimum of twenty ball bearings be tested to provide a sufficient data base.

2. Bearings exhibiting a severe "wear-in" exhibited failures much sooner than their calculated L_{10} life. This observation suggests that a more thorough investigation of causation be performed in order to identify more precisely this relationship.

3. Various quantities of metallic and non-metallic particulate were observed in the unused grease samples. Definition of the possible deleterious nature of this contaminant is desirable from a tribological viewpoint, regarding the effects these particles have on the wear/life of a component.

4. Additional study with respect to the migration of wear debris, particularly the larger (10 micron and above), within the bearing, is required for an adequate understanding of the wearing process of grease lubricated bearings.

VIII. REFERENCES

- (a) Dalal, H. M. et al., "Progression of Surface Damage and Oil Wear Debris Accumulation in Rolling Contact Fatigue", SKF Report AL75T007, April 1975.
- (b) NAVAIRENGCEN Report NAEC-92-133 of August 1979. "Failure Progression Monitoring by Wear Debris Analysis in Grease Lubricated Bearings," Prepared by SKF Inc., under Contract No. N68335-77-C-0584.
- (c) Tessman, R. K., Fitch, E. C., "The Survivability Characteristics of Fluid Power Components in Contaminated Environments," Office of Naval Research, Annual Report on Contract No. N00014-75-C-1157 (1976).
- (d) NAVAIRENGCEN Report NAEC-92-129 of April 1979: "Wear Particle Analysis of Grease Samples," prepared by Foxboro Company, under Contract No. N68335-76-C-2281.
- (e) NAVAIRENGCEN Report of July 1976: "Wear Particle Atlas," prepared by Foxboro/Transonics, Incorporated, under contract No. N001-56-74-C-1682.
- (f) Bowen, E. R., Senholzi, P. B., "Oil Analysis Research," National Conference on Fluid Power (1976).

NAEC-92-152

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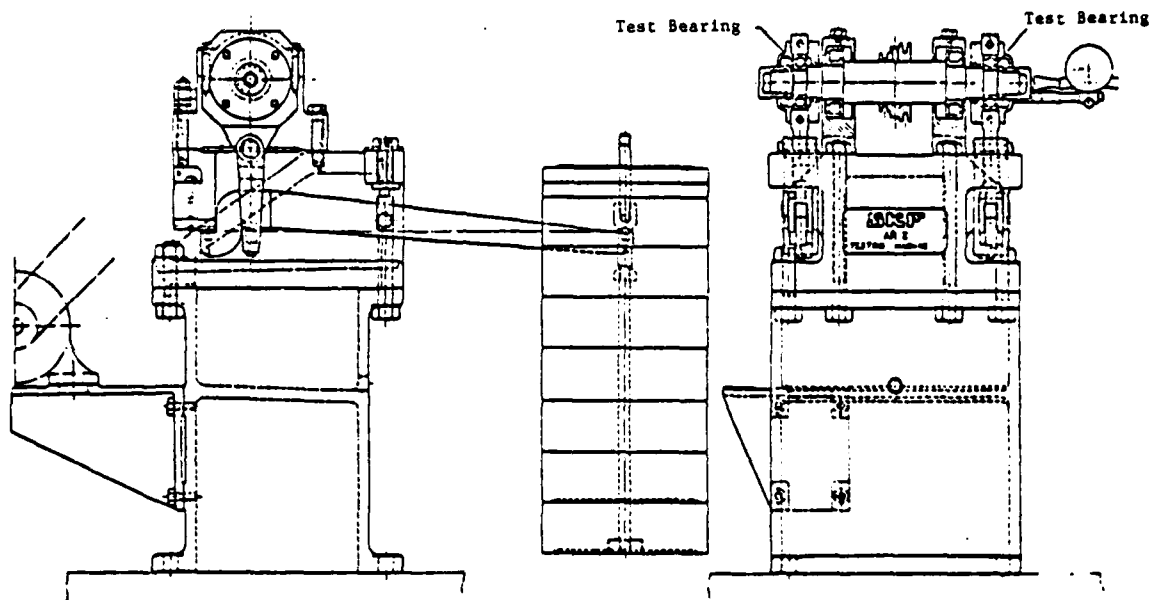


Figure 1 Layout Drawing of R2 Test Rig

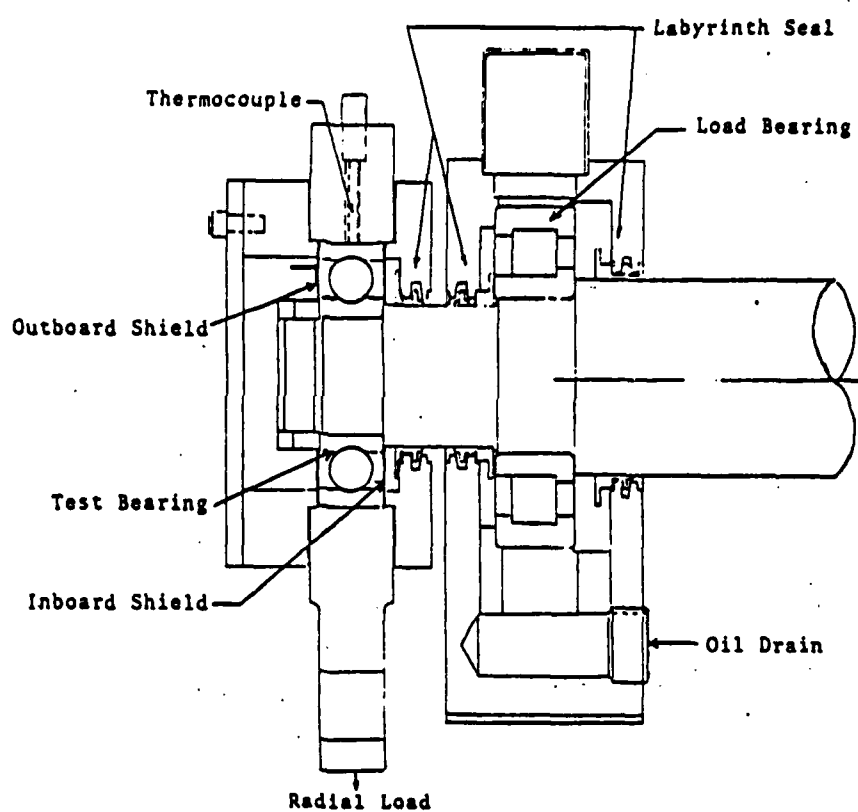


Figure 2 Detailed Drawing of R2 Test Head

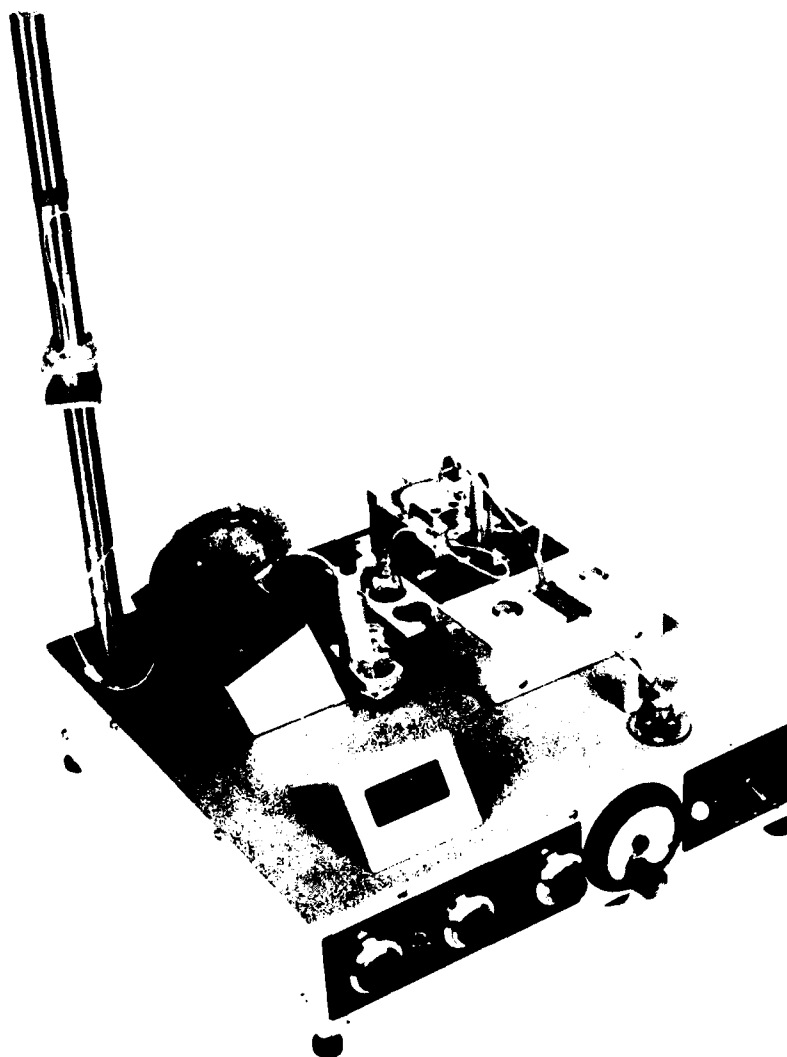


Figure 3 Duplex Ferrogram Analyzer

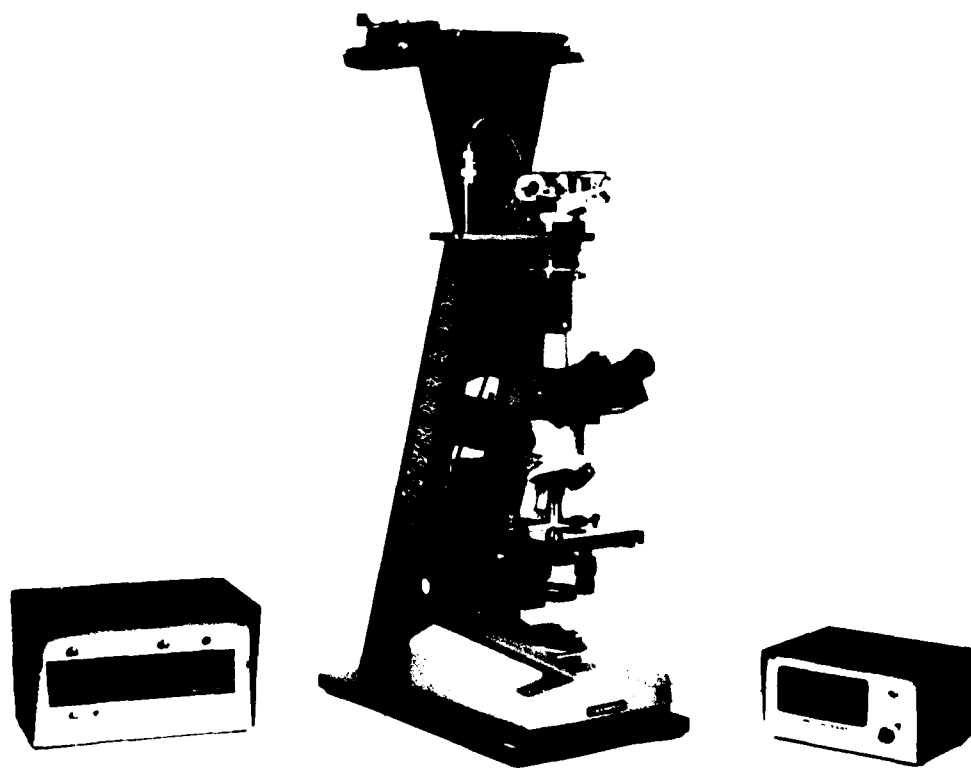


Figure 4 Ferroscope (Bichromatic Microscope)
with Density Reader

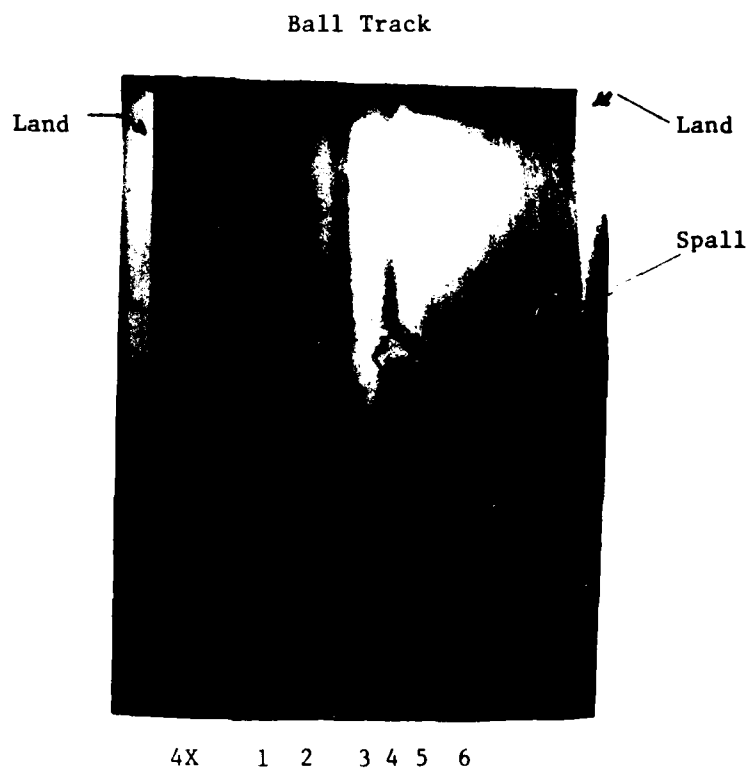
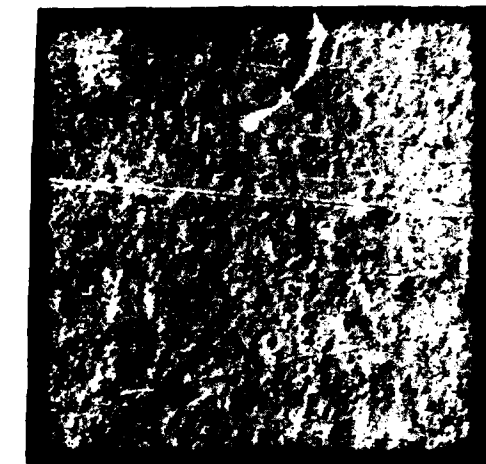


Figure 5 Photomicrograph of Inner Ring of Bearing 01
at Test Termination - 103×10^6 Revolutions

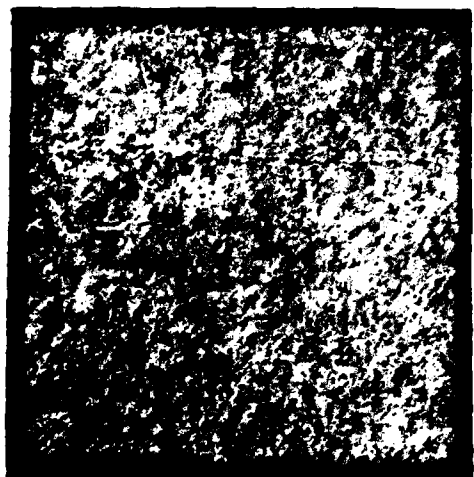


6629

#5

Heathcote Band

500X



6627

#3

Heathcote Band

500X

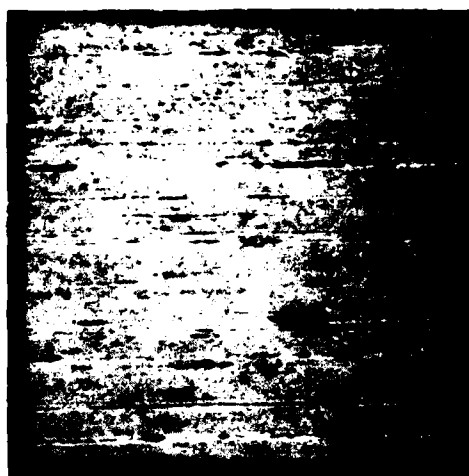


6628

#4

Center Slip Band

500X



6630

#6

Outer Slip Band

500X



6626

#2

Outer Slip Band

500X

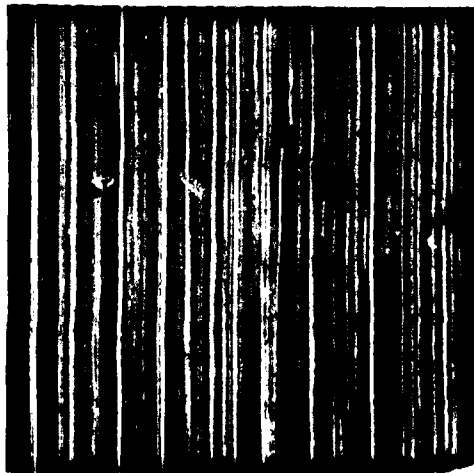
Figure 6 Photomicrographs of Various Areas on Bearing 01



50X

6624

Figure 7 Spall on Inner Ring of Bearing 01



500X

6625

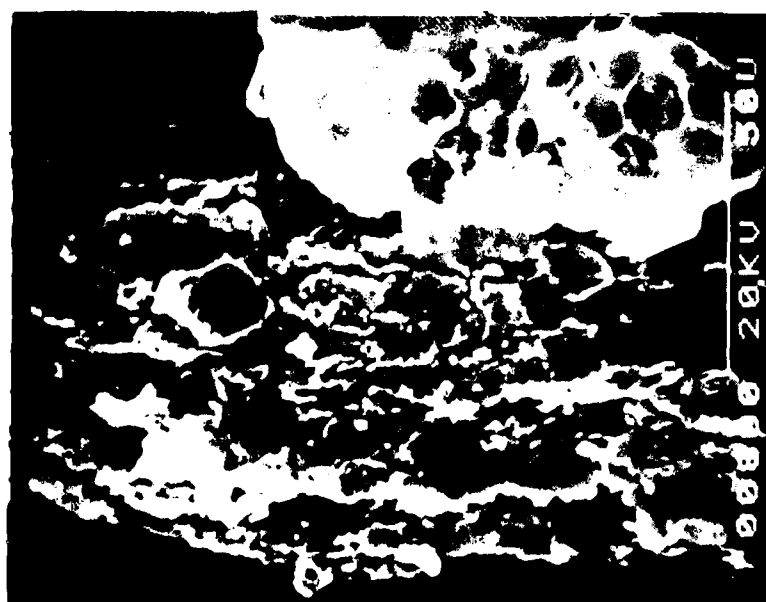
Figure 8 Photomicrograph of Original Surface
of Bearing 01



560X

A

F-2086



800X

B - SEM photomicrograph

F-2086

Figure 9 Photomicrograph and SEM Photomicrograph of Ferrogram From Bearing of Case Ball Sample, After 103 Million Revolutions

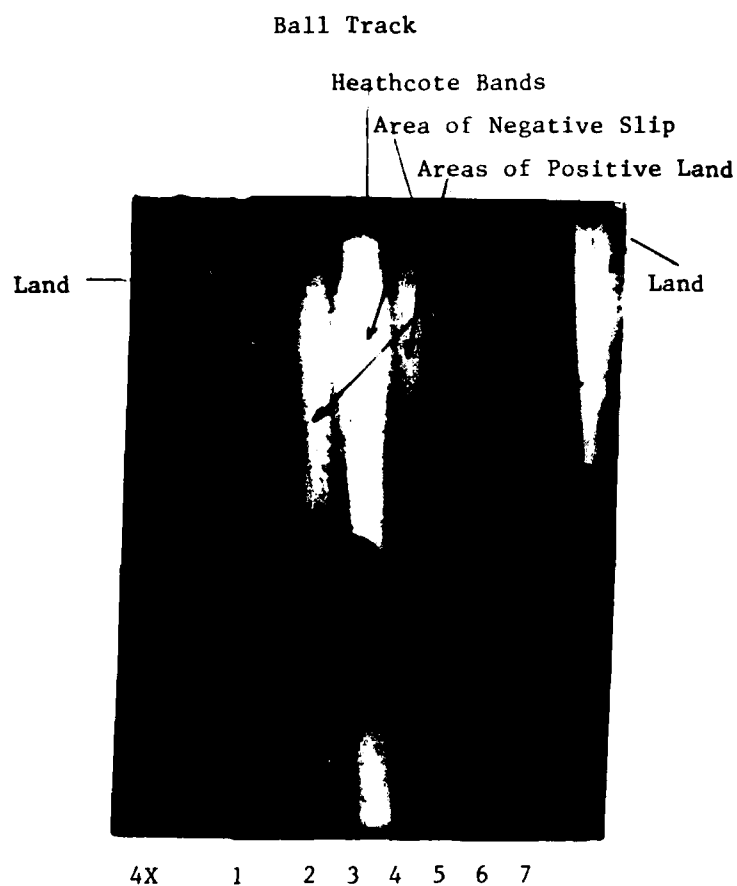
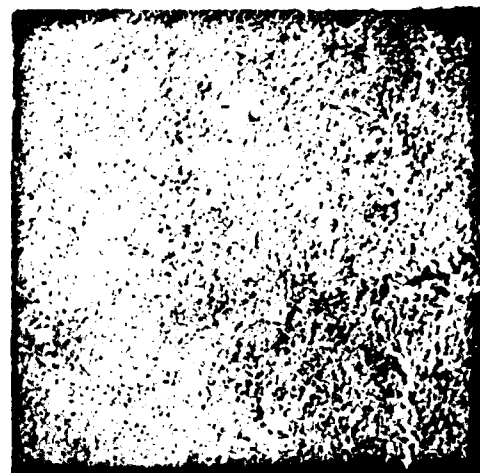


Figure 10 Photomicrograph of Inner Ring of Bearing 02
at Test Termination - 98×10^6 Revolutions



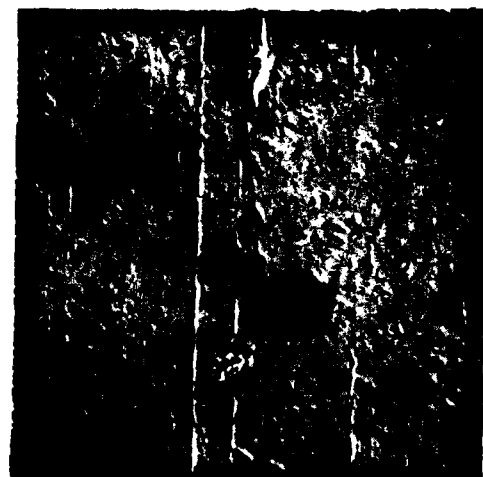
500X A-#4 6633
Center Slip Band



500X B-#3 6632
Heathcote Band



500X C-#5 6634
Heathcote Band



500X D-#2 6631
Outer Slip Band

Figure 11 SEM Photomicrographs of Various Areas of Bearing 02
(Sheet 1 of 2)

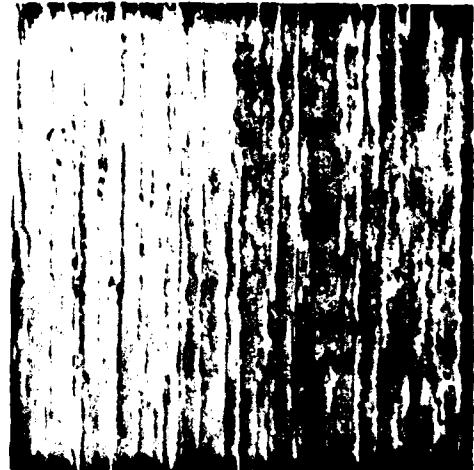


500X

E-#6

6635

Outer Slip Band

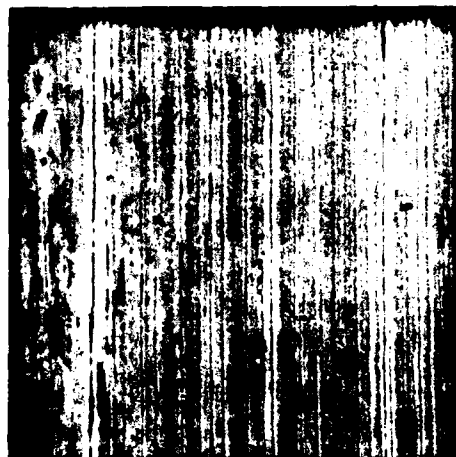


500X

F-#1

6630

Outer Edge of Outer Slip Band



500X

G-#7

6636

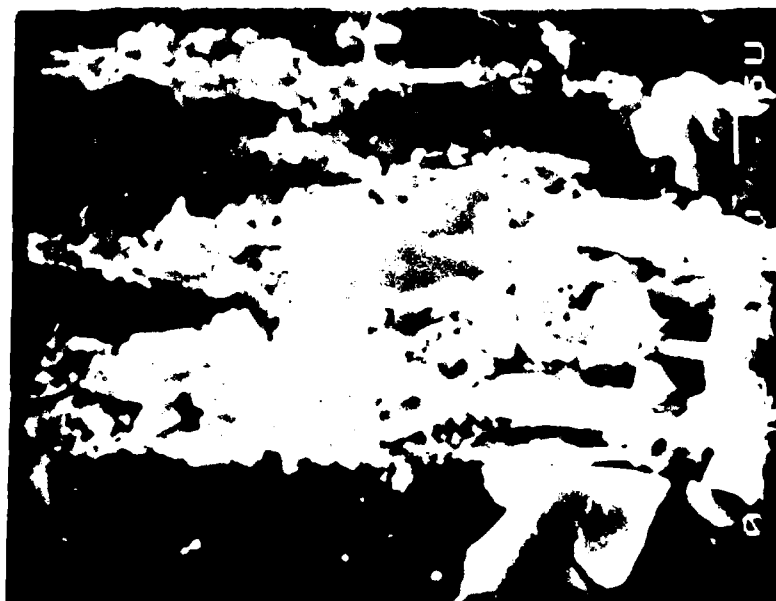
Outer Edge of Outer Slip Band

Figure 11 Photomicrographs of Various Areas of Bearing 02
(Continued - Sheet 2 of 2)



560X

F-21B3



2000X

B-SEM Photomicrograph

F-21B3

Figure 12 Photomicrograph and B-SEM Photomicrograph of Ferrogram From Bearing 02 Cavity Sample, After 98 Million Revolutions

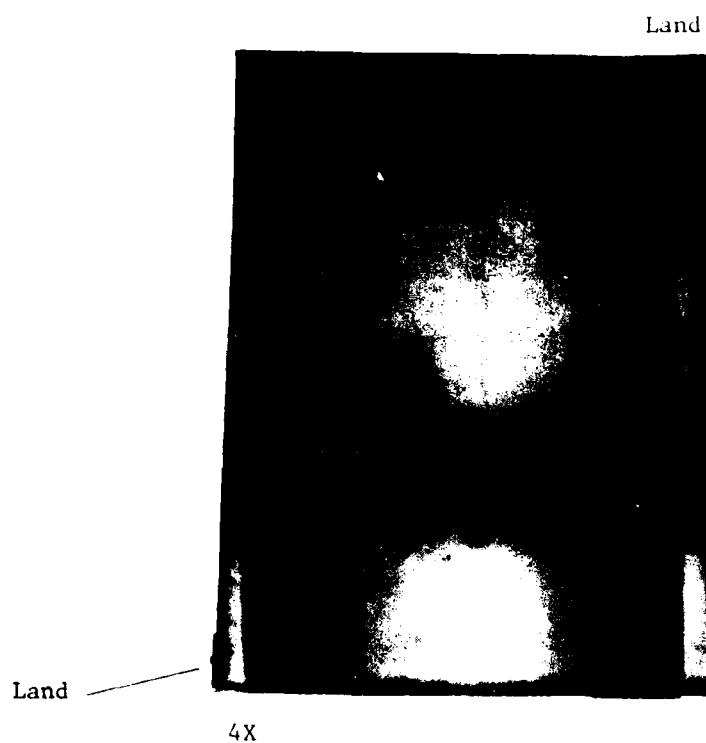
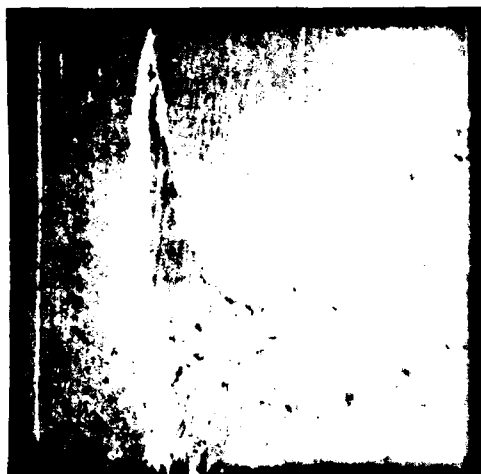


Figure 13 Photomicrograph of Inner Ring of Bearing 03
at Test Termination - 231×10^6 Revolutions



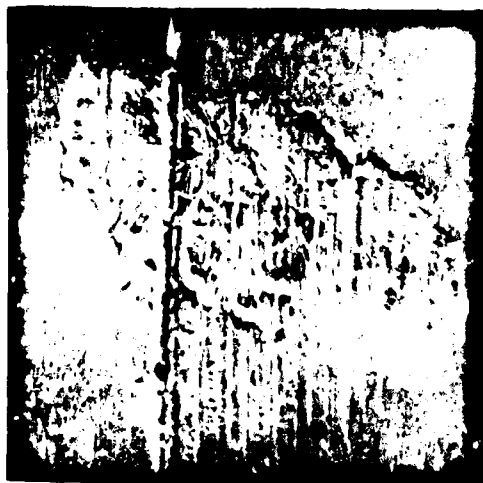
500X A 6686

Gouge in Surface of Inner Ring
(Azimuth Angle 82°)



500X B 6687

Multi-Fragment Dent in Inner Race
(Azimuth Angle 172°)



500X C 6689

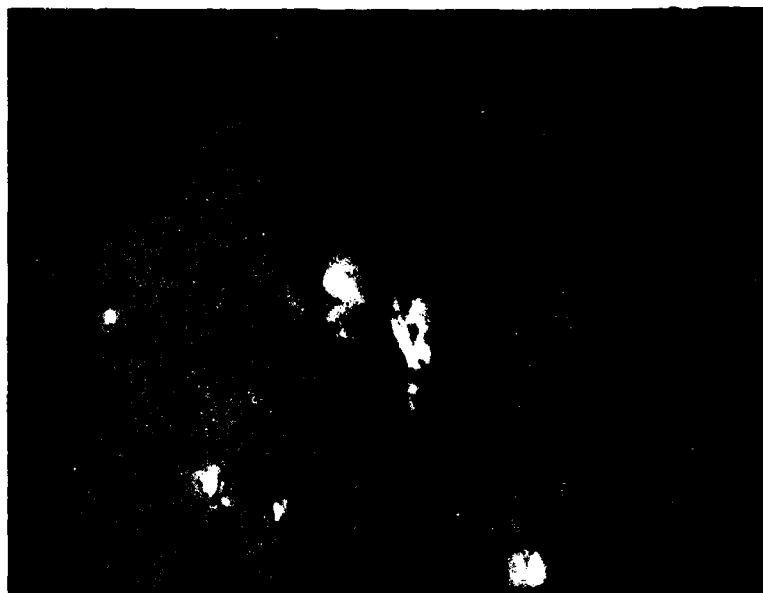
Multi-Fragment Dent in Inner Race
(Azimuth Angle 334°)



250X D 6688

Dents in Inner Race
(Azimuth Angle 182°)

Figure 14 Photomicrographs of Bearing 03



560X

A

F-20X2

After 1 Million Revolutions



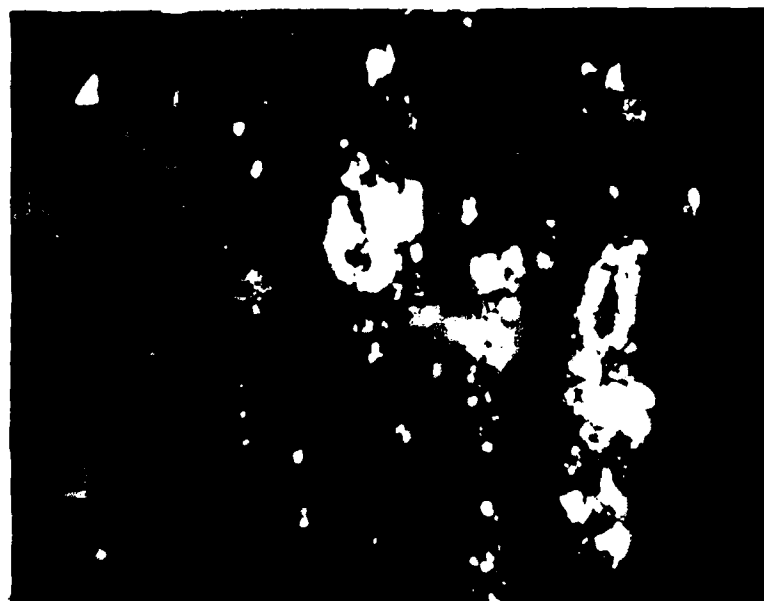
560X

B

F-16B2

After 80 Million Revolutions

Figure 15 Photomicrographs and SEM Photomicrographs of Ferrograms From Cage/Ball Sample, Bearing 03 After Various Revolutions (Sheet 1 of 2)

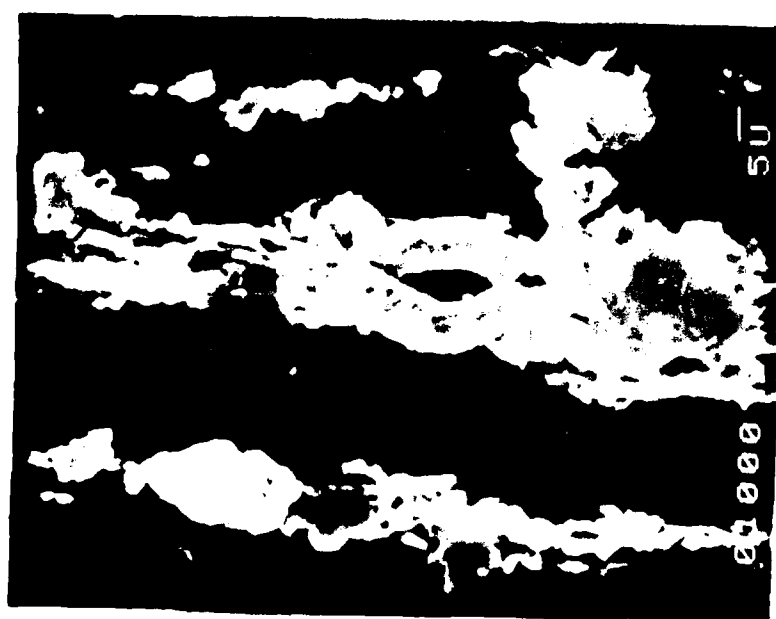


560X

C

F-21C1

After 231 Million Revolutions



1000X

D - SEM Photomicrograph
After 231 Million Revolutions

F-21C1

Figure 15 Photomicrographs and SEM Photomicrograph of Ferrograms
From Case/Ball Sample, Bearing 03
(Continued - Sheet 2 of 2)

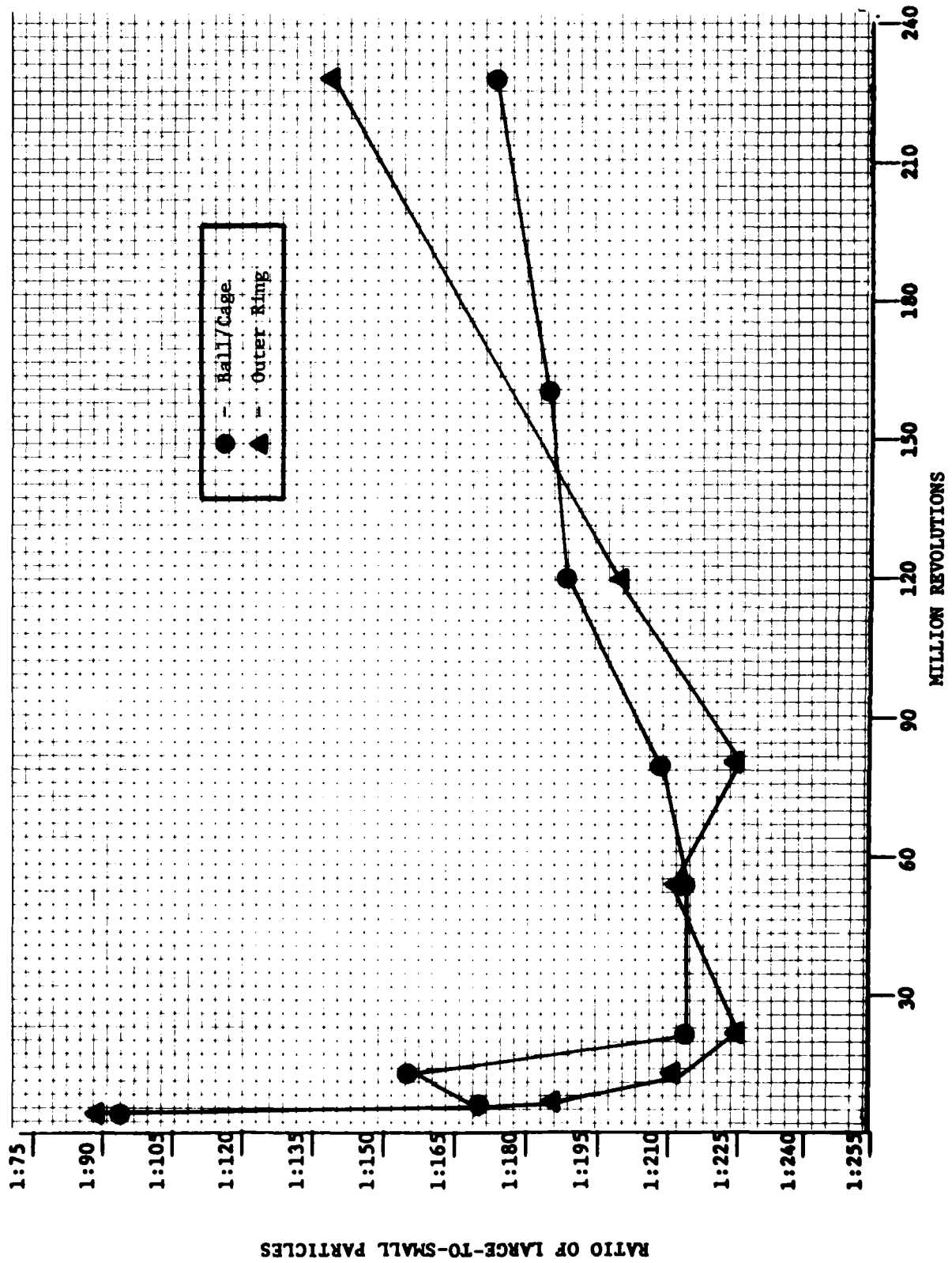
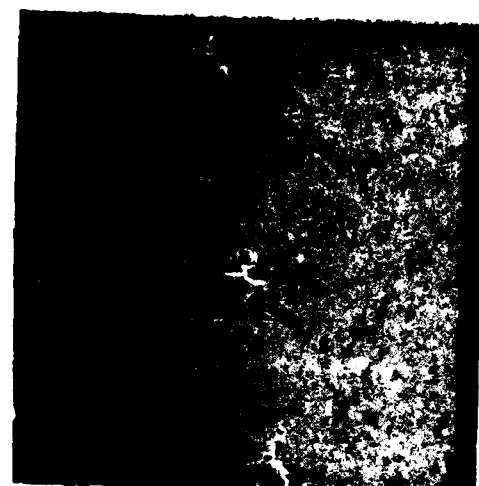


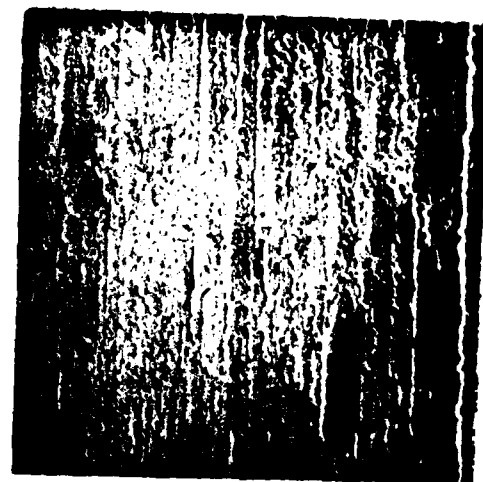
Figure 16 Ratio of Large-to-Small Particles, Bearing 03



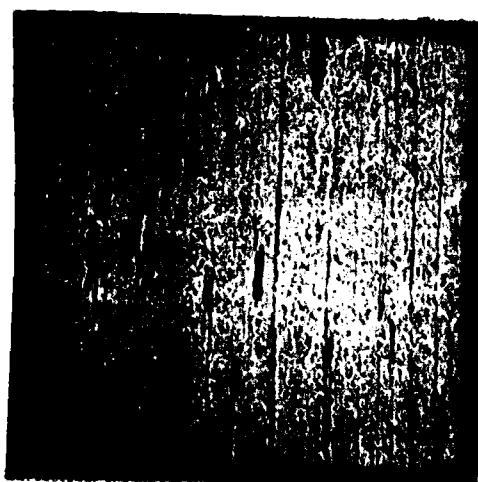
Figure 17 Photomicrograph of Inner Ring of Bearing 04



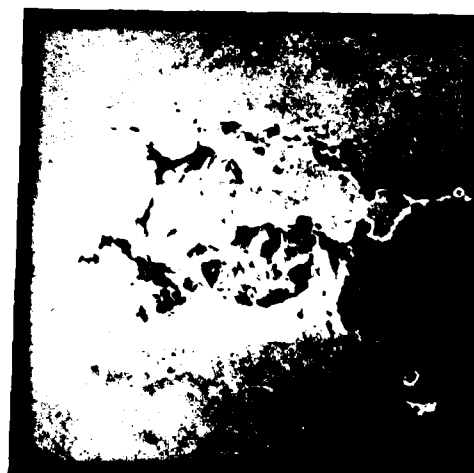
500X A 6692
Center Slip Band



500X B 6691
Outer Slip Band



500X C 6693
Outer Slip Band



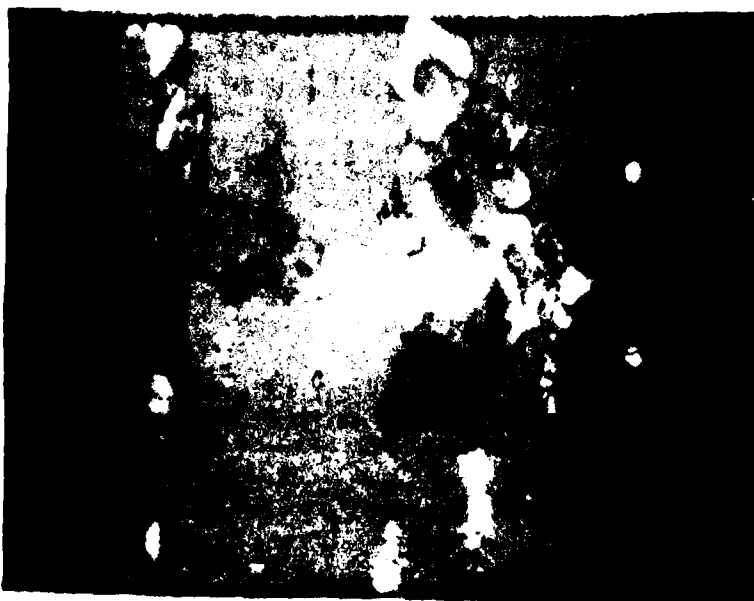
250X D 6696
Spall in Inner Ring

Figure 18 Photomicrographs of Various Areas of Bearing 04



1000X

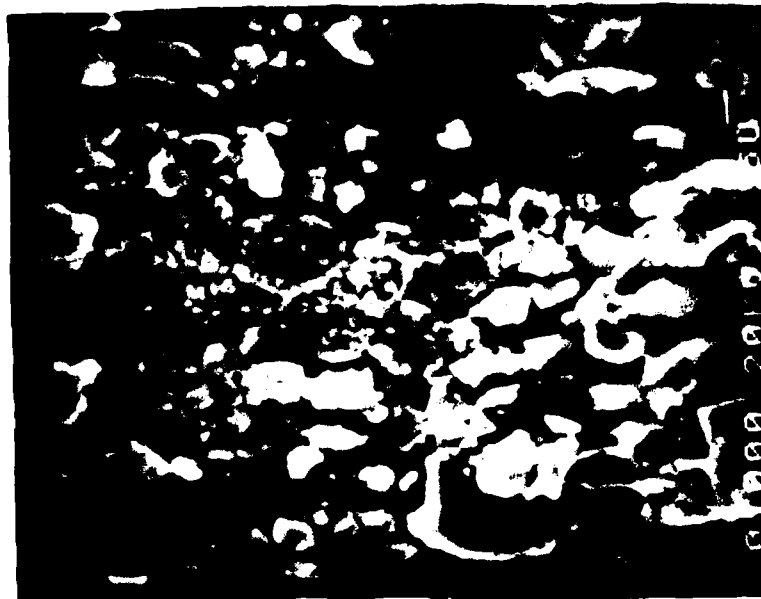
F-22A2



560X

F-19B2

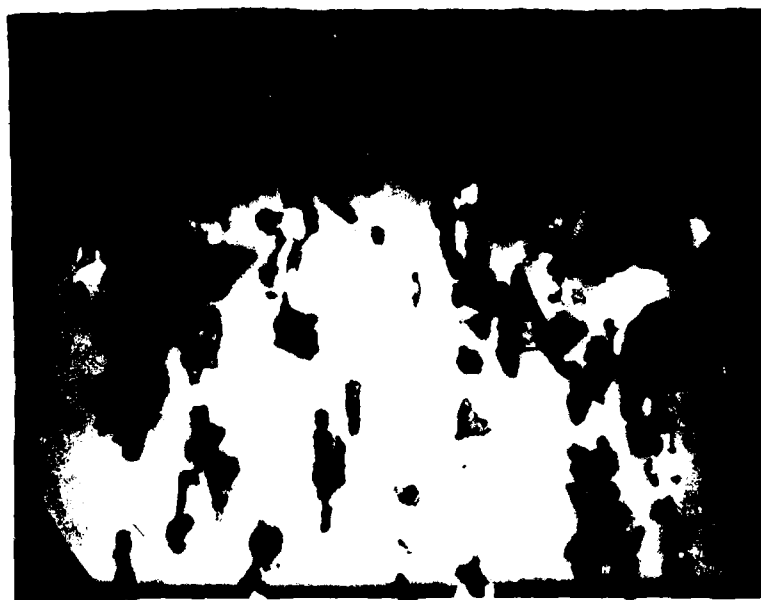
Figure 19 Photomicrographs of Ferrogram From
Revolutions



1000X

C - SEM Photomicrograph
After 231 Million Revolutions

F-20A1



560X

D

F-20A1

After 231 Million Revolutions

Figure 19 Photomicrographs and SEM Photomicrograph of Ferrograms From
Bearing 04 Cage/Ball Sample, After Various Revolutions
(Continued - Sheet 2 of 2)

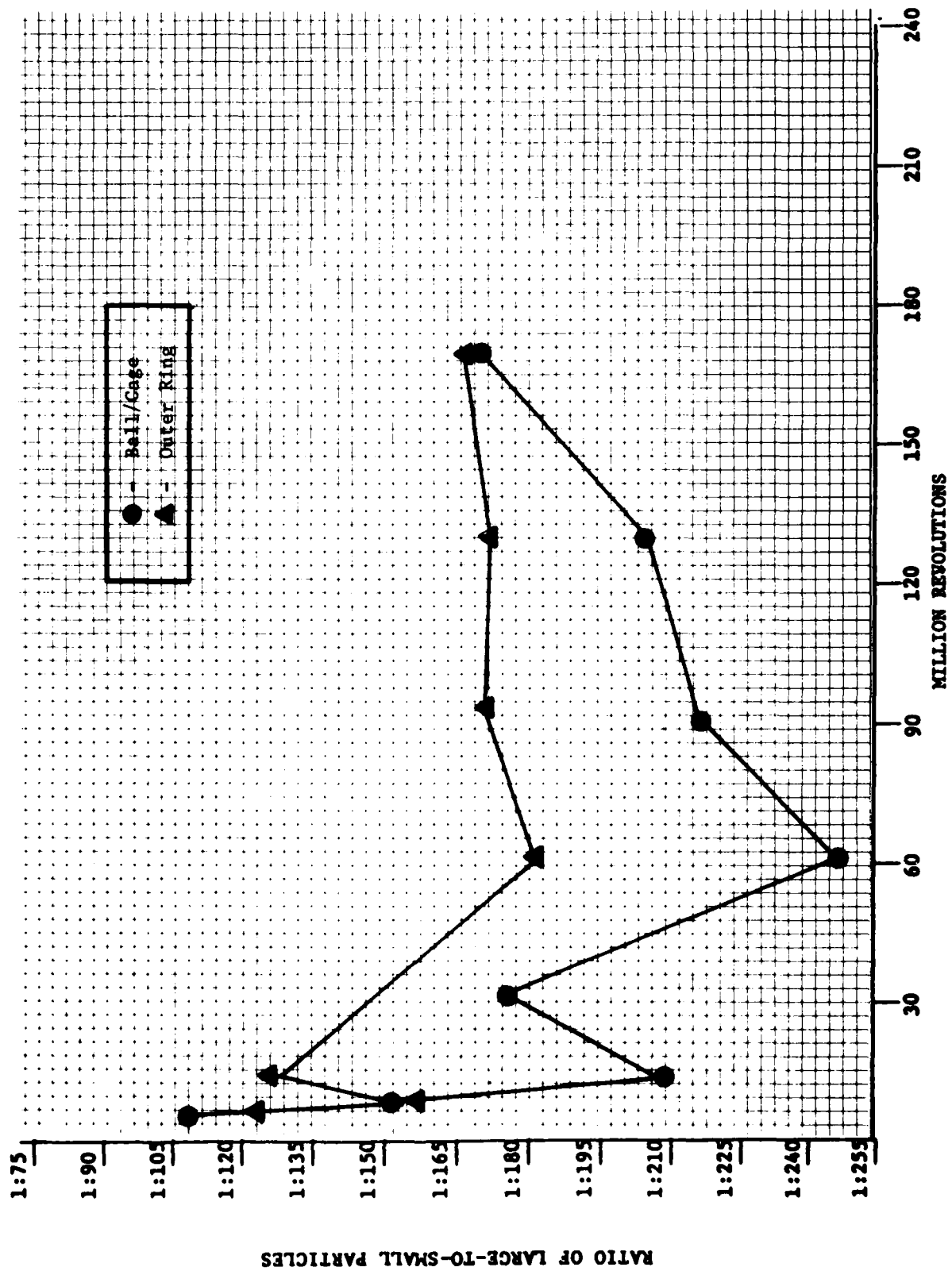


Figure 20 Ratio of Large-to-Small Particles, Bearing 04

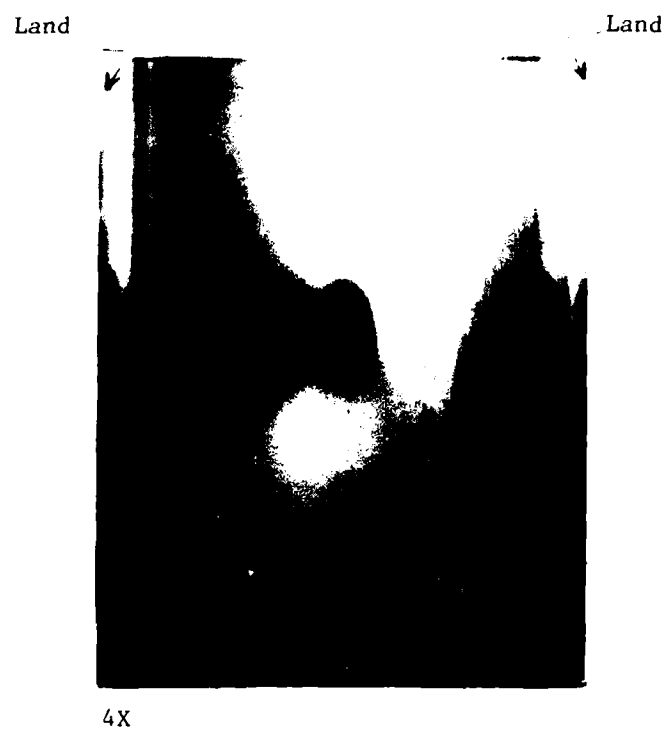


Figure 21 Photomicrograph of Inner Ring of Bearing 05
After 20 Million Revolutions



500X

A

6641

Azimuth Angle 122°



250X

B

6642

Azimuth Angle 214°



500X

C

6645

Azimuth Angle 244°

Figure 22 Photomicrographs of Bearing 05 Showing Multi-Fragment Dents
After 20 Million Revolutions



500X A 6806
Azimuth Angle 122°

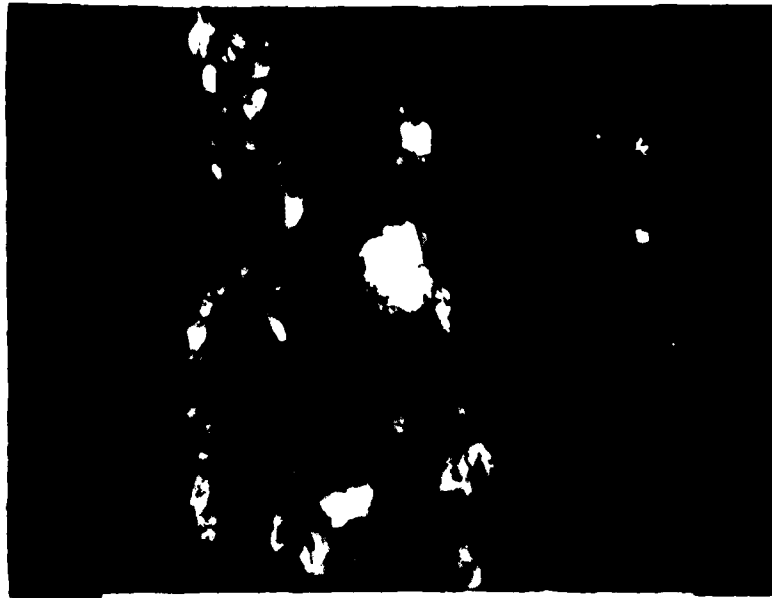


250X B 6808
Azimuth Angle 214°



500X C 6810
Azimuth Angle 244°

Figure 23 Photomicrographs of Bearing 05 Showing Multi-Fragment Dents
After 230 Million Revolutions



560X

F-20D2

Figure 24 Photomicrograph of Ferrogram From Bearing 05
Cage/Ball Sample, After 1 Million Revolutions

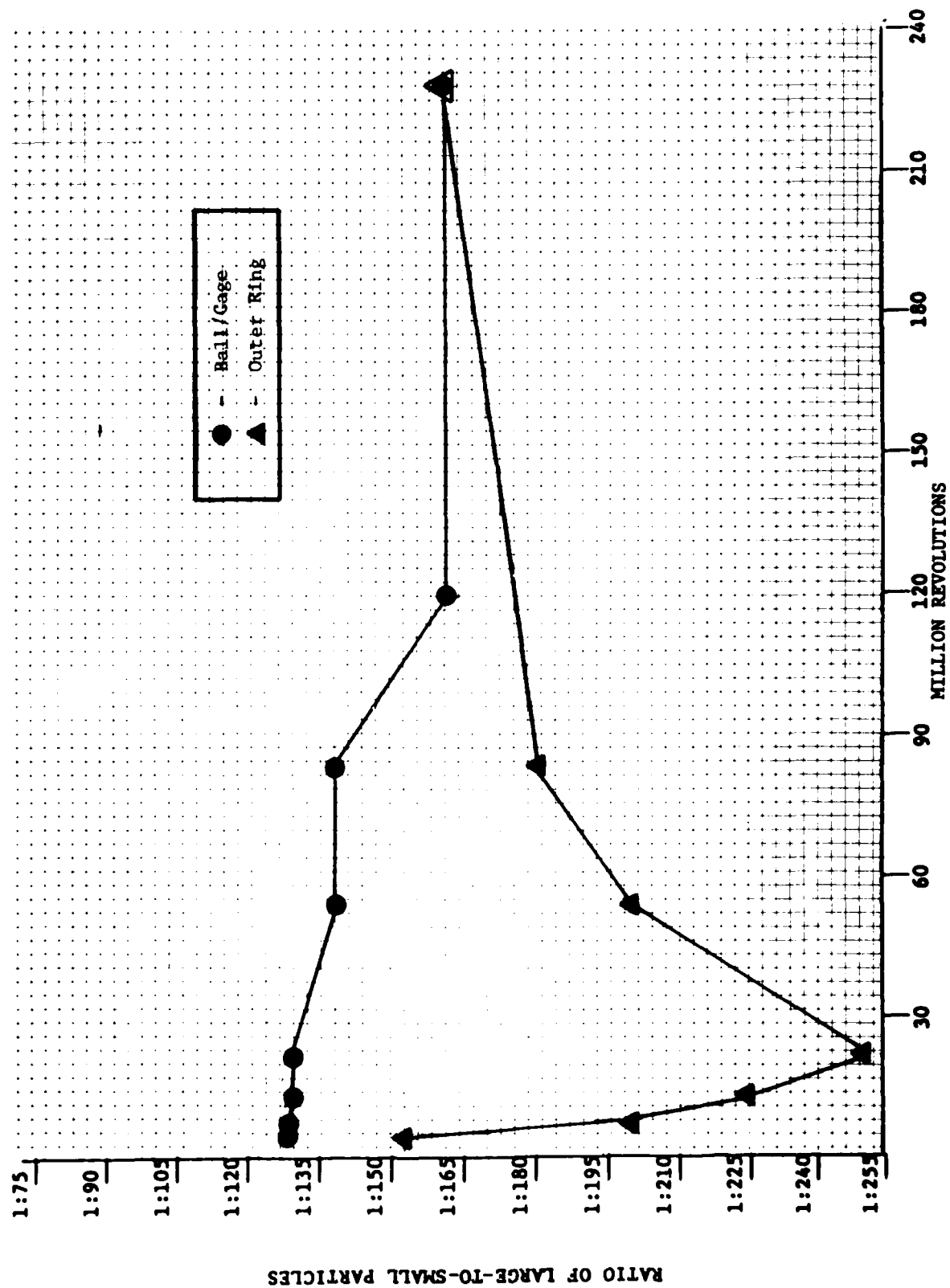
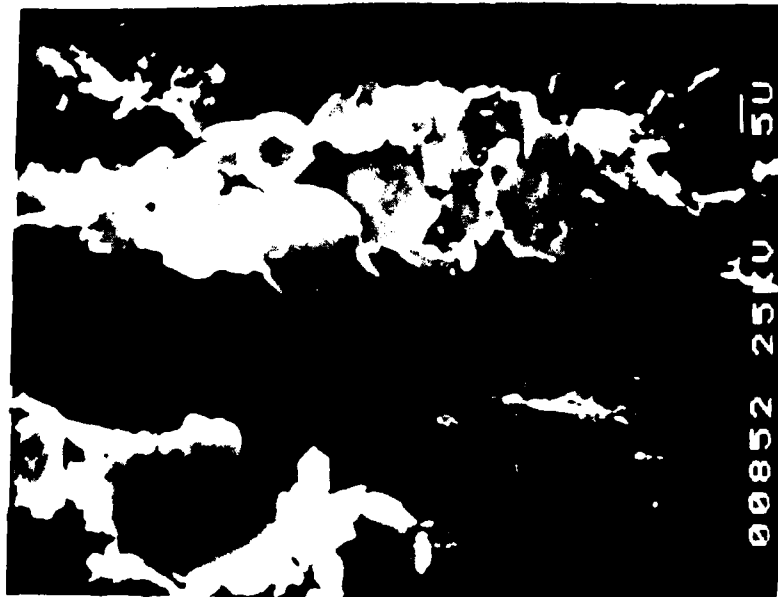


Figure 25 Ratio of Large-to-Small Particles, Bearing 05



850X

A

1-2-92

After 1 MILLION Revolutions



560X

B

1-2-92

After 5 MILLION Revolutions

Figure 26 Photomicrographs of 304 Stainless Steel Bearings from Bearing 15 of the Ball Bearings After 100,000 Revolutions (Sheet 1 of 2)



850X

Micrograph of a
Bearing Surface After
Various Revolutions

F-2031



560X

Micrograph of a
Bearing Surface After
Various Revolutions

F-1130

Figure 26 Photomicrographs of Bearing Surfaces of Ferrogram From
Bearing Surface After Various Revolutions
(Continued from Fig. 25)



1000X

E - SEM Photomicrograph

F-1130

Figure 26 SEM Photomicrograph of Ferrograms From Bearing 05
Cage/Ball Sample, After Various Revolutions
(Continued - Sheet 3 of 3)

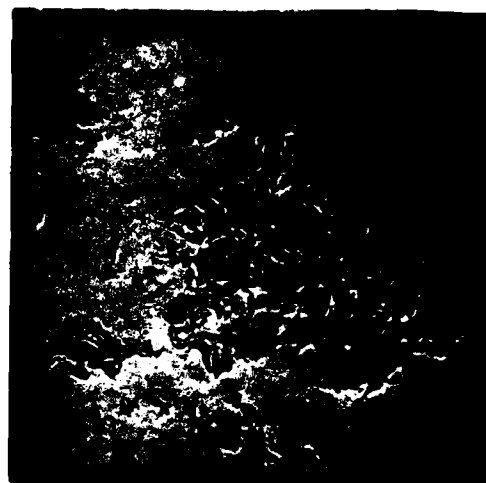


4X

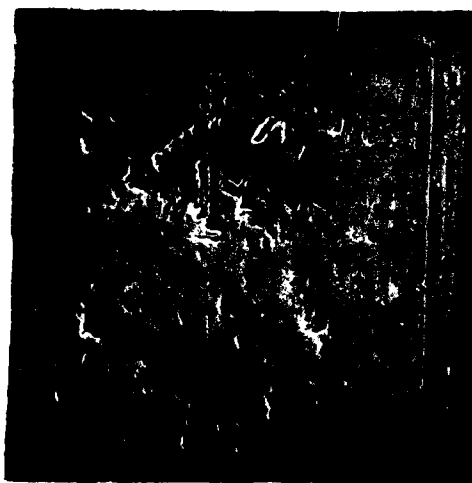
Figure 27 Photomicrograph of Inner Ring of Bearing 06
After 20 Million Revolutions



250X A 6649
Azimuth Angle 30°



500X B 6651
Azimuth Angle 234°



250X C 6652
Azimuth Angle 270°



250X D 6653
Azimuth Angle 340°

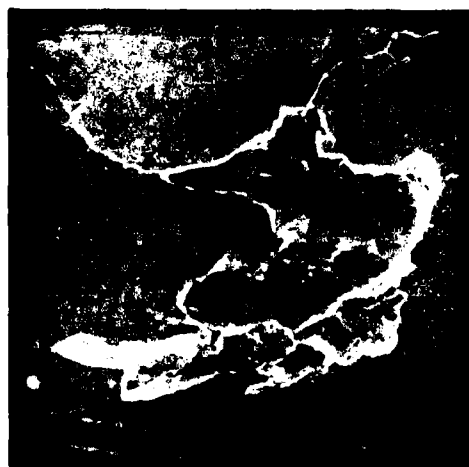
Figure 28 Photomicrographs of Bearing 06 Showing Multi-Fragment Dents
After 20 Million Revolutions



4X

6664A

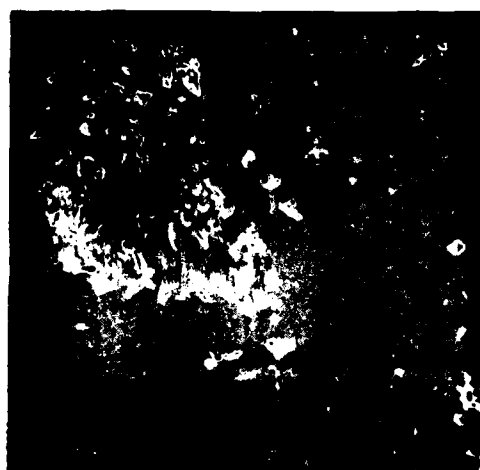
Figure 29 Photomicrograph of Inner Ring of Bearing 06
After 52 Million Revolutions



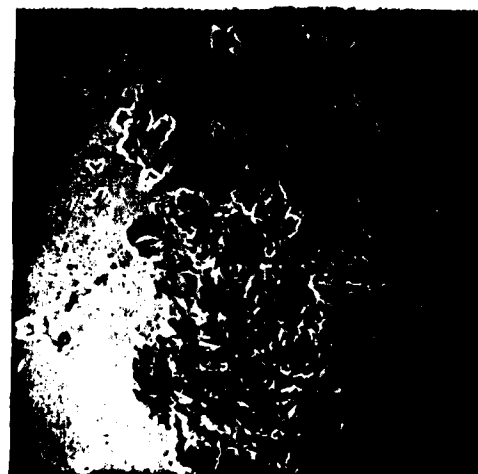
25X

666

Figure 30 Spall in Inner Ring of Bearing 06 After 52 Million Revolutions
(Azimuth Angle 114°)



250X A 6665
Azimuth Angle 30°



500X B 6668
Azimuth Angle 234°



250X C 6669
Azimuth Angle 270°



250X D 6670
Azimuth Angle 340°

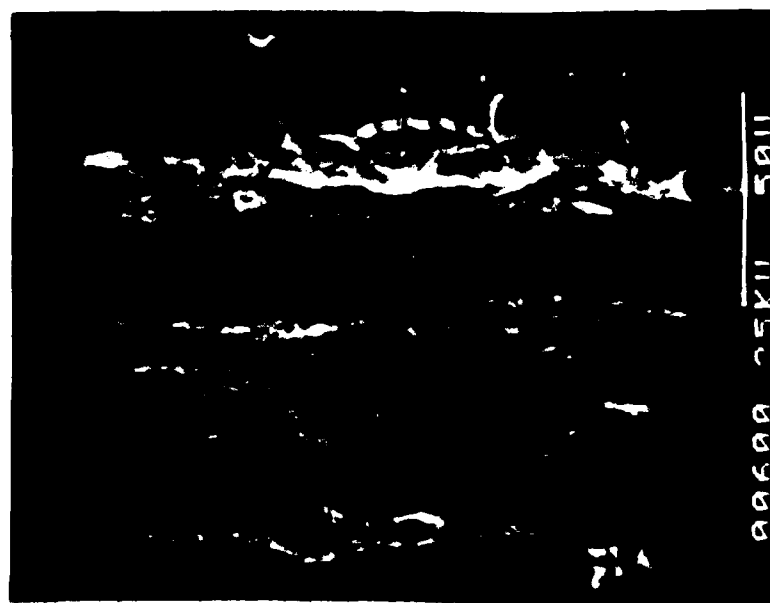
Figure 31 Photomicrographs of Bearing 06 Showing Multi-Fragment Dents
After 52 Million Revolutions



560X

A

F-19A3



600X

B. 1000000 Revolutions

F-19A3

Figure Photomicrographs of the surface of a bearing from a bearing on the F-19A3 engine after 1000000 revolutions



4000X

F-19A3

Metallic surface showing wear



4000X

F-19A3

Metallic surface showing wear

Figure 33 SEM Photomicrographs of a Ball Sample Showing Metallic and Nonmetallic Debris After 1 Million Revolutions

F-2212

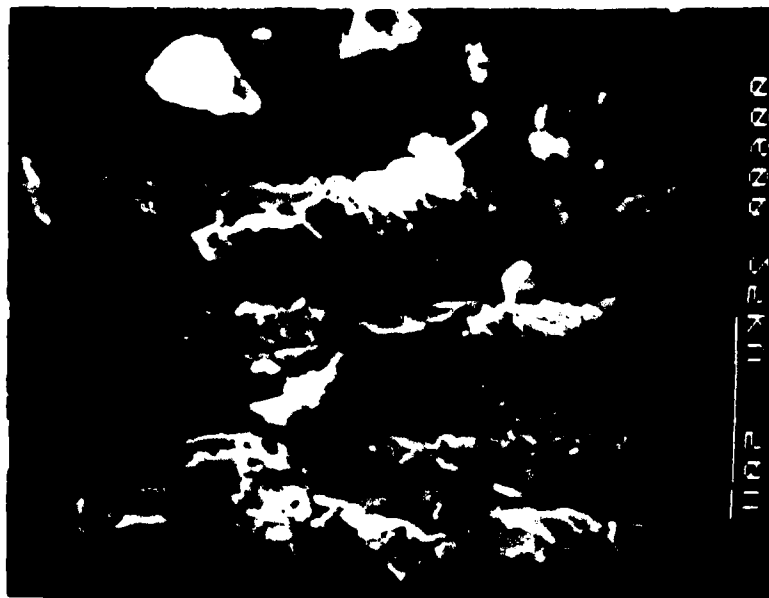


Figure 1. The effect of the concentration of the H_2O_2 solution on the amount of the released H_2O from the H_2O_2 -loaded hydrogel. The amount of the released H_2O was measured by the weight difference of the hydrogel before and after the release. The concentration of the H_2O_2 solution was 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, and 1.0 wt. %.

F-2212

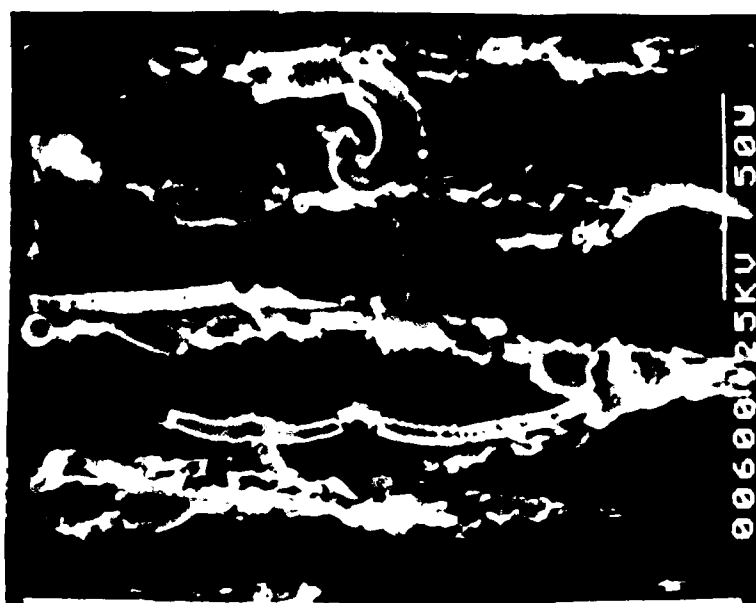
Figure 34 Photomicrograph of PMMA on a Ferrogram From
Bearings of a Cold Chisel, After 10 Million Revolutions



600X

A

F-1172



600X

B - SEM Photomicrograph

F-1172

Figure 35 Photomicrograph and SEM Photomicrograph of Ferrogram From Bearing 96 Ball Cage Sample, After 32 Million Revolutions

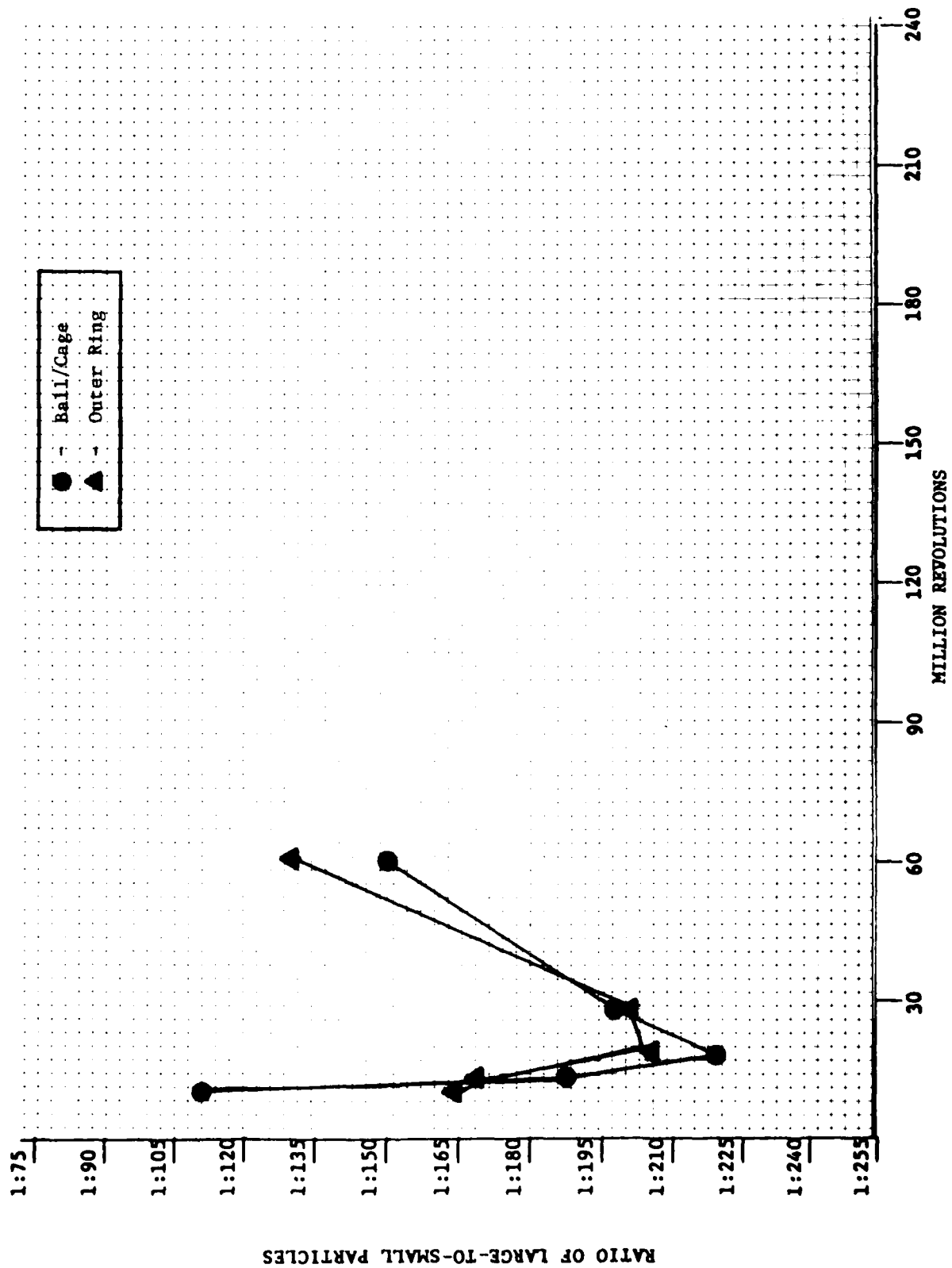


Figure 36 Ratio of Large-to-Small Particles, Bearing 06



2500x

F-2041

Figure 3. SEM image of bearing surface showing large area of material loss. From Bearing Failure Investigation, 1992, by the author. Reproduced with permission.



2500x

F-2086

Figure 4. SEM image of bearing surface showing large area of material loss. From Bearing Failure Investigation, 1992, by the author. Reproduced with permission.

APPENDIX A
TESTING RECORDS OF GREASE-LUBRICATED
BALL BEARINGS

<u>Table</u>	<u>Bearing</u>	<u>Page</u>
A1	01	A-2
A2	02	A-2
A3	03	A-3
A4	04	A-4
A5	05	A-5
A6	06	A-5

TESTING RECORD OF BEARING 01

Operating Period (Millions of Revo- lutions)	O. R. Temp Min/Max (C°)	Down- time (Hr)	Reason for Downtime	Grease Sample Taken	Bearing Cleaned	Bearing Optical	Inspected Mirr/SEM
0-51	79/83	7	TRIM shutoff on bearing 02				
51-73	79/87	6	" " "				
73-92	83/87	14	High temp shut- off on bearing 02				
92-97	84/86	9	TRIM shutoff on bearing 02				
97-98	83/84	72	" " "				
98-103	81/109		TRIM shutoff and spall; test terminated per established criteria	X	X		X/X

TABLE A2

TESTING RECORD OF BEARING 02

Operating Period (Millions of Revo- lutions)	O.R. Temp Min/Max (C°)	Down- time (Hr)	Reason for Downtime	Grease Sample Taken	Bearing Cleaned	Bearing Optical	Inspected Micr/SEM
0-51	83/113	7	TRIM shutoff				
51-73	87/116	6	" " "				
73-92	91/120	14	High temp shut- off				
92-97	89/116	9	TRIM shutoff				
97-98	89/108		TRIM shutoff and test terminated per established criteria	X	X		X/X

TABLE A3
TESTING RECORD OF BEARING 03

Operating Period (Millions of Revo- lutions)	O.R. Temp Min/Max (C°)	Down- time (Hr)	Reason for Downtime	Grease Sample Taken	Bearing Cleaned	Bearing Inspected Optical Micr/SEM
0-1	77/79	9.4	Take grease sample	X		
1-5	80/82	11.0	" "	X		
5-10	71/78	94.0	" "	X		
10-20	79/83	18.5	" "	X		
20-52	72/93	8.5	" "	X		
52-80	77/96	5.7	" "	X		
80-120	73/81	26.0	" "	X		
120-160	74/82	28.5	" "	X		
160-189	75/80	0.2	TRIM shutoff on bearing 04			
189-205	67/70	3.2	" "	"		
205-208	66/67	15.5	" "	"		
208-225	67/71	66.0	" "	"		
225-231	77/79		Test time-up	X	X	X/X

TABLE A4
TESTING RECORD OF BEARING 04

Operating Period (Millions of Revo- lutions)	O. R. Temp Min/Max (C°)	Down- time (Hr)	Reason for Downtime	Grease Sample Taken	Bearing Cleaned	Bearing Optical	Inspected Micr/SEM
0-1	85/90	9.4	Take grease sample	X			
1-5	87/90	11.0	" "	X			
5-10	78/85	94.0	" "	X			
10-20	86/93	18 5	" "	X			
20-52	90/94	8.5	" "	X			
52-80	88/93	5.8	" "	X			
80-120	85/91	26.0	" "	X			
120-160	87/91	28.5	" "	X			
160-189	87/118	0.2	TRIM shutoff				
189-205	91/121	3.2	" "				
205-208	95/119	15.5	" "				
208-225	92/120	66.0	" "	X			
225-231	92/95		Test time-up	X	X		X/X

TABLE A5

NAEC-92-152

TESTING RECORD OF BEARING 05

Operating Period (Millions of Revo- lutions)	O. R. Temp Min/Max (C°)	Down- time (Hr)	Reason for Downtime	Grease Sample Taken	Bearing Cleaned	Bearing Inspected Optical Micr/SEM
0-1	-	93	Replace grease and inspect	X	X	X/X
1-5	94/95	121	" "	X	X	X/X
5-10	92/95	118	" "	X	X	X/X
10-20	89/95	50	" "	X	X	X/X
20-52	88/91	240	" "	X	X	X/X
52-80	86/93	151	" "	X	X	X/X
80-120	82/88	240	" "	X	X	X/X
120-160	86/91	126	" "	X	X	X/X
160-230	-	-	Test time-up	X	X	X/X

TABLE A6

TESTING RECORD OF BEARING 06

Operating Period (Millions of Revo- lutions)	O.R. Temp Min/Max (C°)	Down- time (Hr)	Reason for Downtime	Grease Sample Taken	Bearing Clea ned	Bearing Inspected Optical Micr/SEM
0-1	-	93	Replace grease and inspect	X	X	X/X
1-5	91/92	121	" "	X	X	X/X
5-10	87/88	118	" "	X	X	X/X
10-20	87/90	50	" "	X	X	X/X
20-52	83/87	240	Vibra-switch shutoff (inner- ring spall); Test terminated per established criteria	X	X	X/X

NAEC-92-152

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APPENDIX B

OPTICAL MICROSCOPE OBSERVATIONS OF TEST BEARINGS

OPTICAL MICROSCOPE OBSERVATIONS OF TEST BEARING
NO. 01 FOLLOWING TEST

Bearing 01 - 317 hours, 103×10^6 revolutions

Inner Ring

Appreciable surface distress, indicating poor lubrication. Ball track readily detectable with five bands clearly evident.

A small spall had occurred with one small piece exfoliated and five cracks extending from outboard side of rolling band into center and opposite outer sliding band. The two Heathcote bands were amber in color due to thermal discoloration with fine finish grinding marks quite obvious. The center microslip band was glazed and frosted in appearance indicating the presence of microspalling. Where the center microslip band merges into the rolling bands on either side the remaining finish lines are more prevalent. The outer microslip bands are glazed with a frosted appearance close to the rolling bands.

Outer Ring

Appreciable surface distress. Ball track readily detectable with five bands clearly evident and extending approximately 270° indicating the load zone. The bands appear very similar to those on the inner ring. The glazing was greater than on the inner at the maximum load area of the center microslip band as indicated by the removal of all finish grind lines. Rolling bands are amber to light blue in color.

Balls

Excellent condition with a few very fine scratch lines.

Cage

Excellent condition, only very minor polishing on the cage pockets.

OPTICAL MICROSCOPE OBSERVATION OF TEST BEARING
NO. 02 FOLLOWING TEST

Bearing 02-302 hours, 98×10^6 revolutions

Inner Ring

Advanced surface distress (worse than 01) indicating poor lubrication. Ball track readily detectable with five bands clearly evident. Both Heathcote bands were dark gray in color due to thermal discoloration with a few fine finish grinding marks still present. Both bands had mottled appearance which appear to be microspalling or chemical etching resulting from lubricant. The center microslip band was highly glazed with some microspalls and no finish grinding marks present. Outer microslip bands highly glazed with mottled appearance which appear to be microspalls. Finish grinding marks increase in density with the distance from center. Light blue-amber thermal discoloration at outer edges of bands.

Outer Rings

Advanced surface distress indicating poor lubrication. Ball track readily detectable with five bands clearly evident and extending approximately 270° . A single band, amber in color, continues over the remaining 90° segment indicating that a thermal imbalance between the inner and outer ring removed the radial play in the bearing at some point during the test. Both Heathcote bands were dark gray in color due to thermal discoloration with fine finish grinding marks still present. Both bands have mottled appearance which appear to be microspalls or chemical etching resulting from lubricant. The center microslip band was glazed with mottled appearance with a very few finish grinding marks present. Outer microslip bands were highly glazed with mottled appearance. No finish marks adjacent to Heathcote bands, but finish marks increase in density with distance from center.

Balls

Mottled appearance over major portion of surface that appears to be the result of chemical etching. Also several discoloration bands light blue to amber in color. A few very fine scratches were also present.

Cage

No particular wear marks except there was minor polishing of edges in ball pockets.

OPTICAL MICROSCOPE OBSERVATION OF TEST BEARING
NO. 03 FOLLOWING TEST

Bearing 03-708 hours, 231×10^6 revolutions

Inner Ring

Excellent condition. Ball track was only slightly evident due to minor plastic flow of asperities which caused the contacted surface to have a slightly higher polished appearance than the uncontacted surface of race. Very few larger size dents which were approximately 0.2 mm in diameter. Many smaller size dents of approximately 0.02 to 0.05 mm in diameter. Finish grinding lines observable over complete ball track.

Outer Ring

Excellent condition. Ball track appeared very similar to the inner ring track and extended approximately 240° around circumference.

Balls

Excellent condition. Only a few fine scratches which were equally dispersed over ball surface.

Cage

Minor wear indicated by polished areas on edges of ball pockets.

OPTICAL MICROSCOPE OBSERVATION OF TEST BEARING
NO. 04 FOLLOWING TEST

Bearing 04-708 hours, 231×10^6 revolutions

Inner Ring

Ball track easily detected with three distinct bands. A center band approximately 4.5 mm wide was highly glazed and two external bands which were gray in appearance. The center band contained the two Heathcote bands of pure rolling which were detectable by a slight discoloration (amber). Many micro-pits and microcracks were present in the glazed center band with no finish grinding lines present. In the outer two bands, the finish lines were quite visible. The general appearance indicated that poor lubrication existed at sometime during the test.

Outer Ring

Race surface similar to inner ring with a multiple band extending for 270° and a single band extending for the remaining 90° . The 360° ball track on the outer ring indicated that the radial clearance had been lost at sometime during the test. This probably resulted from a thermal imbalance between the inner and outer ring which often occurs when poor lubrication exists.

Balls

All balls had discolored (straw to light purple) bands with the major surface area mottled in appearance.

Cage

Minor wear indicated by polished areas on edges of ball pockets.

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OPTICAL MICROSCOPE OBSERVATIONS OF TEST BEARING
NO. 05 AT SPECIFIED INTERVALS

Bearing 05-3 hours, 1×10^6 revolutions

Inner Ring

Race in excellent condition. Could not detect ball track due to changes in finish grinding marks. However, some denting had occurred. The dents were approximately 0.02 to 0.05 mm in diameter. There was also a 360° ring of broken grinding furroughs on the outboard size of the race outside of ball track which occurred during the manufacturing of the ring.

Outer Ring

Very similar to inner with denting density the same.

Balls

Excellent condition, with a few fine scratches distributed over surface.

Cage

No detectable wear.

Bearing 05-15 hours, 5×10^6 revolutions

Inner Ring

Race in excellent condition. Could not detect ball track from changes in finish marks. Denting density appeared to be about three times that after 1×10^6 cycles.

Outer Ring

No observable change from 1×10^6 cycles.

Balls

No observable change.

Cage

No observable change.

Bearing 05-31 hours, 10×10^6 revolutions

Inner Ring

Excellent condition. Ball track was just observable by brighter appearance due to slight change in finish grinding marks caused by plastic flow of asperities. The dent previously described had not changed appreciably in number; however, there were many smaller dents which appear approximately 0.005 mm in diameter. No changes in furrow marks.

Outer Ring

Appeared very similar to inner ring with what appears to be glazing around some of the larger dents.

Balls

No observable change.

Cage

No observable change.

Bearing 05-61 hours, 20×10^6 revolutions

Inner Ring

Excellent condition. Ball track appears essentially the same as after 10×10^6 cycles. Finish grinding marks still present over complete ball track. No banding can be detected, however, the center of the track is slightly brighter indicating more plastic flow of asperities in this area. No detectable change in quantity of dents. A very minor spall also observed. This spall had been detected by the SEM after 1×10^6 cycles. No change had occurred.

Outer Ring

Appeared very similar to inner ring except the plastic flow of asperities appeared to be slightly greater as evidenced by finish grinding marks being slightly less evident.

Balls

No observable change.

Cage

No observable change.

NAEC-92-152

Bearing 05-160 hours, 52×10^6 revolutions

Inner Ring

Good condition with only slight changes in track. There are fingernail shaped dents approximately 1/8" long at 0° , 40° , 95° , 190° , and 275° relative to the bearing marking. Finish grinding marks still prevalent in track with denting density slightly greater. Dents still of two basic sizes. Smaller dent cover essentially all of contact surface. No observable change in furrows. No change in minor spall.

Outer Ring

Good condition and appears very similar to inner ring. Fine fingernail shaped marks approximately 0° azimuth position.

Balls

Discoloration bands on three balls. Fine scratch marks on all balls with 1 or 2 dents per ball. One ball had one fingernail shaped dent similar to those observed on inner and outer rings.

Cage

No observable change.

Bearing 05-245 hours, 80×10^6 revolutions

Inner Ring

Good condition. Could not detect any observable change. The fingernail shaped dents, minor spall, and scuff marks appear the same as after 52×10^6 revolutions.

Outer Ring

Appears very similar to inner. No observable change.

Balls

Discoloration bands on 4 balls, very faint. Normal scratches except for one ball which has a small circle approximately .5 inches in diameter formed by scratches.

Cages

No observable change.

Bearing 05-369 hours, 120×10^6 revolutions

Inner Ring

Race in good condition. Appears essentially the same as after 80×10^6 cycles except center of ball track has slightly more glazed appearance due to further plastic flow of asperities and the density of the dents was also slightly greater. Finish grinding lines still quite prevalent in all parts of the ball track.

Outer Ring

Similar to inner ring.

Balls

No observable change in balls.

Cage

No observable change in cage.

Bearing 05-492 hours, 160×10^6 revolutions.

Inner Ring

Race in good condition. No observable change detected in the fingernail shaped dents, minor spall, or scuff marks. Number of dents have increased with the addition of several micropits which indicate that some metal pulling had occurred. Finish grinding marks or lines quite prevalent in all parts of ball track, but appear less wide or finer indicating further plastic flow had occurred.

Outer Ring

Race in good condition. Appearance and changes very similar to inner ring.

Balls

No observable change.

Cage

No observable change.

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Bearing 05-708 hours, 230×10^6 revolutions

Inner Ring

Race in good condition. Considerably more micropits indicating that metal had been pulled from the race. The number of dents had also increased. Although the finish grinding lines were still visible in all areas of the ball track, they were very fine; thus, indicating that additional plastic flow of asperities had occurred. No banding could be observed in the ball track. No observable change in fingernail marks or furroughs.

Outer Ring

Similar to inner ring with the ball track extending for approximately 270° around the race.

Balls

No observable change in balls with fine scratches randomly located on the surface.

Cage

No observable change.

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NAVAL AIR ENGINEERING CENTER LAKEHURST NJ SUPPORT EQU--ETC F/G 11/9
WEAR DEBRIS ANALYSIS OF GREASE LUBRICATED BALL BEARINGS.(U)
APR 82 A S MACIEJEWSKI, J W ROSENLIB
NAEC-92-152

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OPTICAL MICROSCOPE OBSERVATIONS OF TEST BEARING
NO. 06 AT SPECIFIED INTERVALS

Bearing 06-3 hours, 1×10^6 revolutions

Inner Ring

Race in excellent condition. Could not detect ball track due to changes in finish grinding marks. Denting density and size approximately the same as bearing 05 after 1×10^6 cycles. There were also approximately 6 pits clustered at 0° azimuth relative to bearing number.

Outer Ring

Race in excellent condition and appeared essentially the same as inner except denting density was approximately 1.5 times that on inner.

Balls

Excellent condition with a few fine scratches distributed over surface.

Cage

No detectable wear.

Bearing 06-15 hours, 5×10^6 revolutions

Inner Ring

Race in excellent condition. Ball track was just observable by brighter appearance due to slight change in finish grinding marks caused by plastic flow of asperities. No observable change in larger size dents observed after 1×10^6 cycles; however, there were a few very fine dents which appeared to be approximately 0.005 mm in diameter.

Outer Ring

Race in excellent condition. Ball track just observable. Denting density appears to be slightly higher than on inner.

Balls

No observable change.

Cage

Slight polishing or wear on edges of ball pockets.

NAEC-92-152

Bearing 06-31 hours, 10×10^6 revolutions

Inner Ring

Excellent condition. The only observable change in the ball track was the increase in the number of small dents. The number of small dents appear to be approximately the same as on bearing 05 after 10×10^6 cycles.

Outer Ring

Appears very similar to inner ring except there were more of the larger dents.

Balls

No observable change.

Cage

No observable change.

Bearing 06-61 hours, 20×10^6 revolutions

Inner Ring

Excellent condition. No observed change except that finish grinding lines in ball track were finer in appearance indicating that additional plastic flow of asperities had occurred.

Outer Ring

Number of large dents had essentially doubled in center of ball track, about twice as many as in bearing 05 after the same number of revolutions. Finish grinding lines still present in ball track, but fine in appearance.

Balls

No observable change.

Cage

No observable change.

Bearing 06-160 hours, 52×10^6 revolutions

Inner Ring

A spall had developed in the center of the track at an azimuth location of 260° relative to the bearing marking. Thermal discoloration, light gray to dark gray, had occurred at leading edge of spall. Density of large dents had greatly increased with the largest number in the center 2/3 of ball track. These dents were undoubtedly the result of debris generated by the spall. In addition to the dents, there were several pits which were black in the bottom and had darken areas around the periphery. The finish grinding lines appeared quite fine in the ball track although they were quite prevalent and easily detected. No kinematic banding was present.

Outer Ring

Ball track very similar to that on inner ring except no spall was present and the ball track extend only the normal 270° around the race.

Balls

Each ball had a discolored band, straw to light purple in appearance, on a major circle with several dents in the band. The dent density was less than that on the races. The rest of the surface appeared normal with only fine scratches.

Cage

No observable change in cage.

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0-8