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NAVAL AIR ENGINEERING CENTER LAKEHURST NJ GROUND
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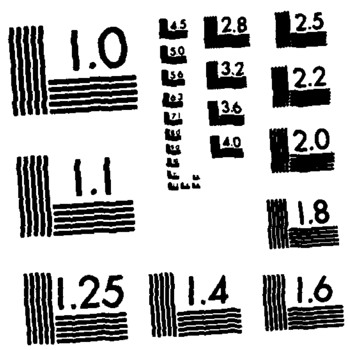

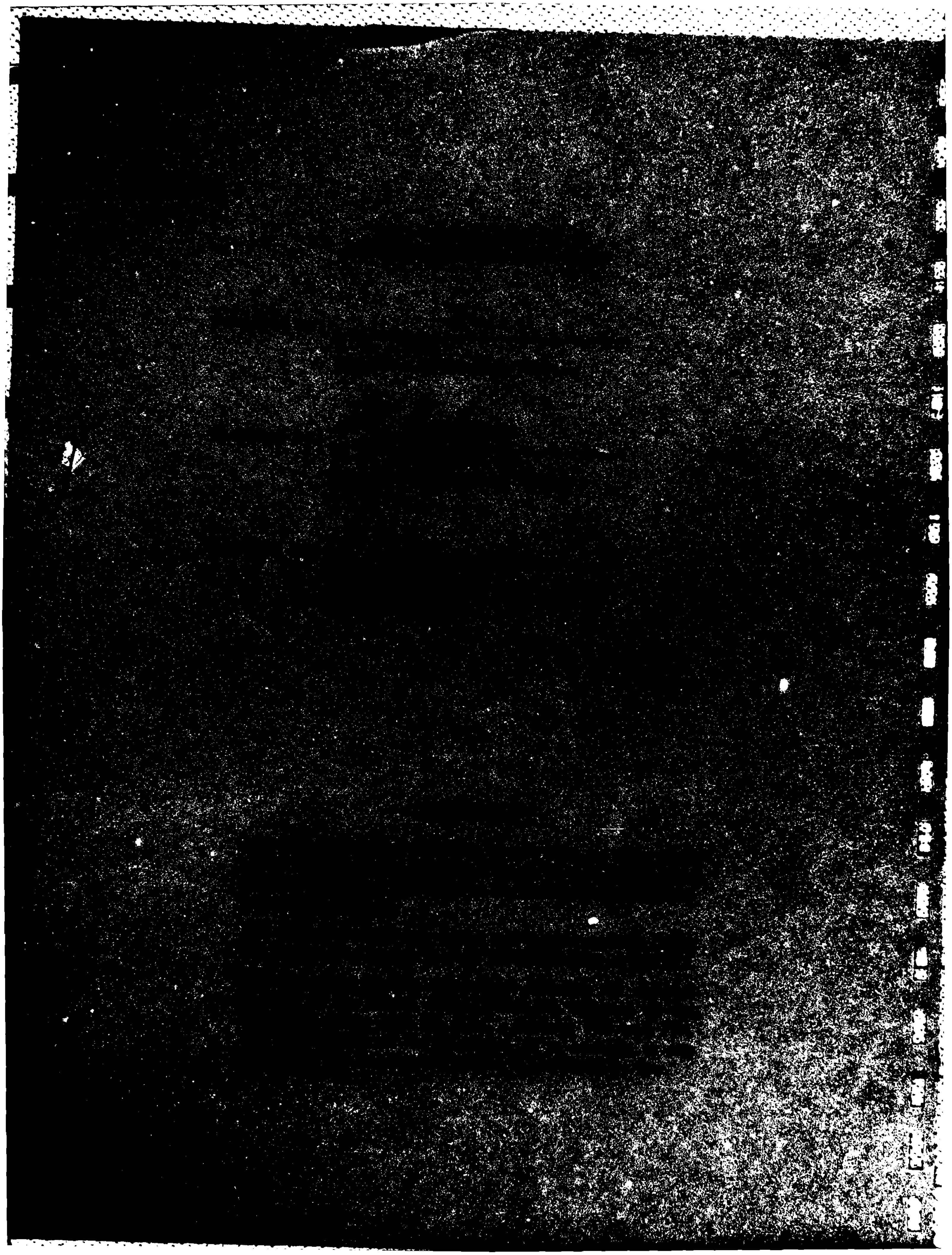

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This report documents a study of the wear debris characteristics of grease-lubricated spur gears. Gear sets were operated in an attempt to correlate the wear state of gears with the wear debris found in the grease. A firm correlation between the two could not be accomplished due primarily to the inability to obtain clear ferrograms from the grease medium.

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PREFACE

The work reported is the final phase of an investigation of the wear debris generation characteristics of grease-lubricated mechanical components. SKF Technology Services designed, fabricated, and operated the test apparatus to generate the debris-laden grease samples and performed optical examination of the gear wear surfaces under Contract N68335-79-C-0530.

The ferrographic analysis and wear correlations were performed by the NAVAIRENGCEN Tribology Laboratory.

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I. INTRODUCTION

A. In an experimental program, research was conducted at the Naval Air Engineering Center's (NAVAIRENGCEN's) Tribology Laboratory, in conjunction with SKF Technology Services, in a combined effort to assess/develop techniques in the field of mechanical system health monitoring of grease-lubricated spur gears. The objective of this program was to investigate means by which the unexpected failure of gears could be reduced in the field by monitoring the wear debris content of the grease. Instead of routinely replacing components during maintenance checks, the extent of the wear state of gear parts could be assessed and replacements made only when necessary. This would mean cost savings in relation to equipment breakdown, parts, and man-hours.

B. Ferrography, the method of analyzing the size, concentration, and morphology of wear particles contained in a lubricant, was chosen as the method to use in this program. It was expected that the use of this method to periodically analyze grease samples taken from gearboxes in service would identify the onset of gear failure prior to its occurrence.

C. The grease samples were analyzed and evaluated at the NAVAIRENGCEN, and an attempt was made to correlate the results with the surface examination of the gears as assessed at SKF using a scanning electron microscope.

II. EQUIPMENT AND TEST PROCEDURES

A. TEST FACILITY

1. The testing was performed at SKF using a four-square gearbox test rig which is four right-angle gearboxes interconnected into a single loop driven from a single power source. This test rig was constructed using commercially available gearboxes used in typical Navy applications. The gearbox is a single staged unit, containing two spiral bevel gears producing a two-to-one speed reduction, with the ability to be driven from either shaft in either direction.

2. Load was created in all four boxes by locking a torsional preload in the interconnected shafts. The preload was applied using a special coupling inserted into one of the legs which produces a finite rotation of one end of the coupling with respect to the other end. The magnitude of the load applied was measured using a calibrated strain-gauge bridge located on another interconnecting shaft. The transmission of moment loads into the gearset as a result of misalignments in the system was prevented by universal joint couplings used to connect each gearbox with the interconnecting shafts. Power, to overcome frictional losses in the loop, was provided by a 20-horsepower, 835-RPM, alternating current motor. This motor was coupled to one double-ended gearbox shaft through a V-belt/pulley system. Test speeds could be varied by altering the pulley ratios.

3. The four-square system has advantages over the more typical method of modeling both power source and demand. A considerably smaller motor can be used since the basic loading torque is conserved in the loop and only friction losses in the loop are replaced. In the other method, the gear loading energy would need to be dissipated in a power absorbing unit. Four gearsets can be tested simultaneously and infinite variations in torques are available. However, wear of gears and bearings does cause measurable decreases in torque levels within test periods as short as 24 hours. Test loads can also vary as different sets of teeth come into mesh.

4. Two-to-one speed reduction gearboxes which could be driven from either shaft in either direction were used, which added flexibility to the test arrangement. Four gearboxes could be run at identical speed and load by connecting the low-speed shaft of the initial gearbox to the low-speed shaft of the second gear unit. Then the high-speed shaft of the second gear unit was connected to the high-speed shaft to the third gearbox. The low-speed shaft of the third unit drove the low-speed shaft of the fourth; and the high-speed shaft of the fourth unit was connected to the high-speed shaft of the initial gearbox. In this manner, all four gearboxes were interconnected to form a loop. This configuration is shown in the schematic in Figure 1.

5. During operation, gear condition was monitored by observing temperatures and vibration. Grease temperature was measured near the point of mesh by a thermocouple. A Data General computer monitored thermocouple output and would give an alarm if any temperature increased at a given rate or reached a preset temperature. If the temperature rose at a high rate or reached a second temperature, the computer would stop testing.

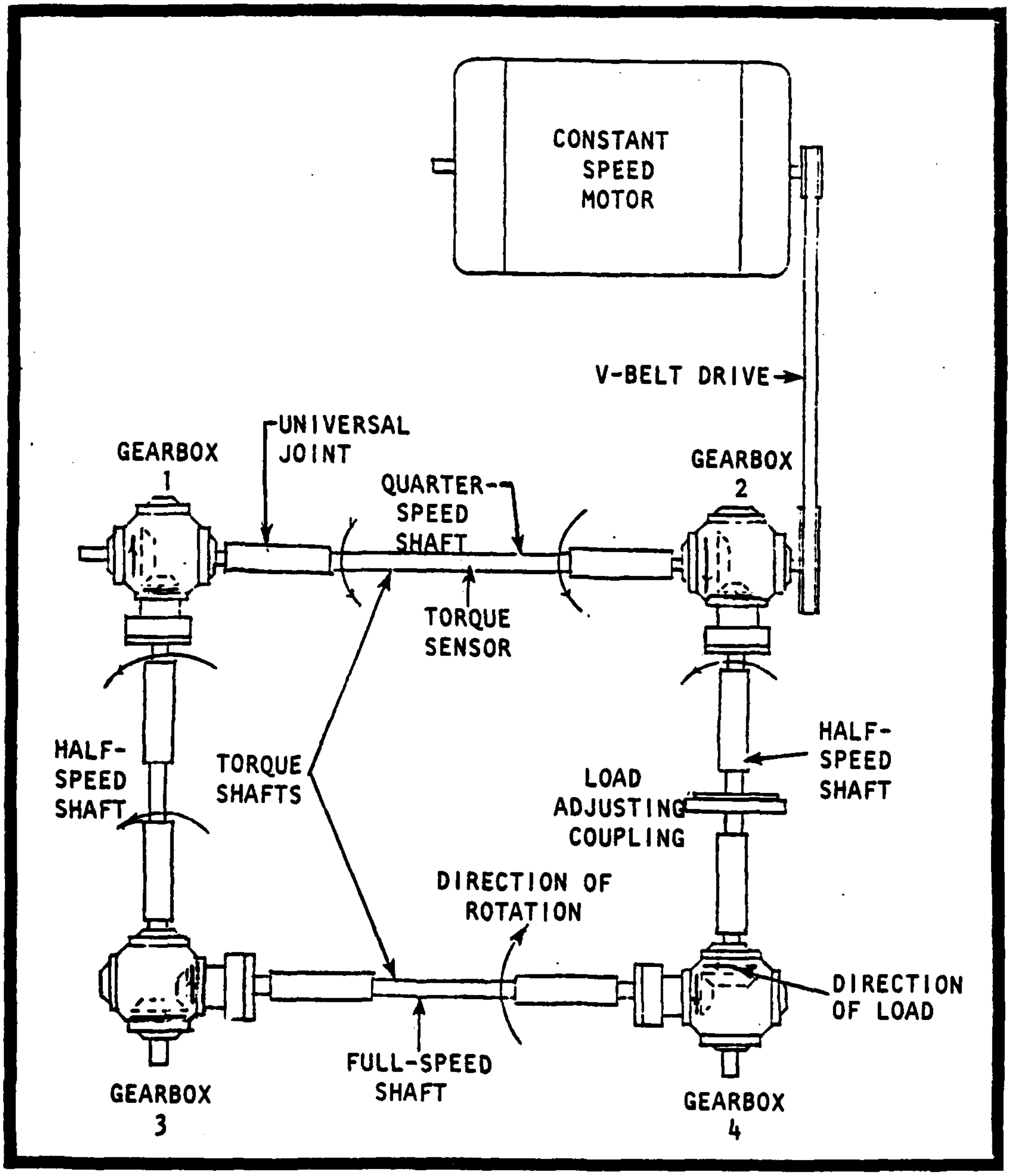

FIGURE 1. SCHEMATIC OF FOUR-SQUARE GEARBOX TEST RIG

6. A mechanical vibration switch was also wired into the motor circuit. Vibration magnitudes in excess of the normal operating band would thereby halt testing. This feature protected against failure of the test specimen and numerous rig components.

7. Exxon Ronex MP grease was chosen (mutually by NAVAIRENGCEN and SKF) as the gear lubricant, based on its excellent lubrication properties and its compatibility with known Ferrography techniques. Grease was packed into the gearbox until the level was even to the top of the lowest gear. This left the larger gear approximately 80 percent out of the grease pack.

B. TESTING

1. PRELIMINARY TEST RUNS

a. The initial portion of testing was conducted to develop a test procedure which would generate typical gear surface fatigue failures in a reasonable test period The primary gearboxes were initially set at a load based on the manufacturer's recommendations. Successive tests were then run at loads based on data gained in the previous test, until an acceptable failure mode and test period was obtained.

b. The subsequent tests were run under the conditions developed in the initial series to establish a wear failure history on sets of gears. During this testing, the four-square rig was assembled so that all four gear sets would run under identical loads and speeds, two with direction of rotation coinciding with the direction of load application on the pinion, and two with the direction of rotation opposing the direction of load.

2. FINAL PHASE

a. The final phase of testing dealt with the running of four fresh gear sets to generate a typical life wear profile at 5 points. The four-square rig was assembled with all gearboxes running at the same speed. In this configuration, gear positions 1 and 3 are under identical conditions with both pinions rotating in the same direction under identical magnitude and direction of load Gearbox positions 2 and 4 are also under identical conditions. Positions 1 and 2 are used as test specimens, and 3 and 4 are used as controls. All four gearboxes ran at 57.5 rad/sec (550 RPM) and 10.9 Nm (100 in. lb) of torque on the low-speed shaft.

b. During this final phase of testing, two distinct tests were conducted:

(1) Tests 1 and 2 (Gearboxes 1 and 2)

(a) These tests were conducted to correlate the accumulation of wear debris in grease with the accumulation of gear tooth surface damage. Testing was to be interrupted at five intervals. and at each shutdown the gears were removed, tooth wear measured, and face surfaces examined for deterioration. The gears were regreased with unused grease, reinstalled in the gearbox; testing continued until the next shutdown period or test termination.

(b) Gearbox 1 failed after 14,807,000 gear revolutions (18.6 days at 550 RPM) due to heavy smearing. Gearbox 2 failed after 26,976,000 gear revolutions (34.0 days at 550 RPM); again, due to heavy smearing.

(2) <u>Tests 3 and 4 (Gearboxes 3 and 4)</u>

(a) These tests were conducted to obtain a time profile of wear debris accumulation and grease pack deterioration, allowing a minimum degree of interference with the established grease pack kinematics. Testing was to be interrupted at five intervals, and at each shutdown the gearbox was to be partially disassembled and grease samples removed from the teeth faces, roots, and sides over a fixed segment of the gear. New grease was to be added into the areas from which the sample was removed in approximate equivalent volumes with minimum disturbance of the residual grease until the next shutdown period at which time grease was removed from a different gear segment. This procedure was to be continued until test time was up or gear failure. At this time, gears were removed, all grease extracted, and the gear teeth measured for wear and examined for deterioration visually and using the SEM.

(b) Gearboxes 3 and 4 had a life of 29,614,000 gear revolutions (37.4 days at 550 RPM) and did not fail. Testing was terminated for time-up.

(c) Only those grease samples from gearboxes 3 and 4 of this final phase of testing were analyzed at the NAVAIRENGCEN.

III. WEAR PARTICLE ANALYSIS

A. GENERAL. The technology of wear particle analysis, which has been successfully applied as a nondestructive indicator of surface wear in oil-lubricated equipment, can also be utilized for grease-lubricated components. Since the grease is contained within the component, generated wear debris will also remain within the component. Therefore, the wear debris contained in a grease sample is representative of the specific component, or more precisely, of the actual segment of the component where the sample was obtained.

B. SAMPLE PROCESSING. In order to ferrographically analyze the grease samples, the grease first had to be dissolved. The ferrographic equipment utilized required the grease to be dissolved into a fluid-type composition so it could pass through the thin tubing onto the glass slide. At the same time, an acceptable ferrogram was required to analyze the wear particles.

C. SOLVENT EVALUATION. Solvent #2 was selected to dissolve the grease and as a washer/fixer solution. This solvent is composed of 33 percent toluol, 33 percent methyl ethyl ketone, and 34 percent isopropanol. Its selection was based on previous studies conducted at NAVAIRENGCEN, which have shown Solvent #2 to be more effective with "worked" grease in that the ferrograms were virtually free of residual grease material as opposed to the other solvents.

D. TEST SAMPLING. Grease samples were removed at five time intervals: 191 hours, 380 hours, 565 hours, 735 hours, and 950 hours. Three sampling locations were used on both pinion and gear of each gearbox:

1. Location 1 - Tooth end at small diameter
2. Location 2 - Tooth contact surface
3. Location 3 - Tooth end at large diameter

The position of the initial sample was recorded by placing a mark on the drive pulley in alignment with a stationary mark. Grease was then removed from the uppermost tooth or teeth. Subsequent sample locations were established by rotating the pinion in a predetermined direction, three teeth from the previous sample.

E. PREPARATION PROCEDURE. The following procedure was used in the preparation of the grease samples for ferrographic analysis:

1. Ten 3-mm-diameter glass beads were placed in a 1/2-ounce super clean bottle to aid in the agitation process of the grease solution.

2. Used grease varying in weight between .001 gm and .0840 gm was added to the bottle using a teflon-coated spatula. The varying weights of the grease depended on visual examination of the color of the grease to determine extent of wear deposits, that is, darker colored grease samples were prepared with smaller amounts of grease, etc. In some cases, the availability of grease provided by the contractor precluded using this method and all grease provided was used.

3. Five cc of Solvent #2 was poured into the bottle. The bottle was capped and vigorously hand shaken until it was observed that all the grease was dispersed.

4. Five cc of filtered MIL-L-23699, a synthetic ester based fluid, was added to the dispersed grease mixture to increase its viscosity index to aid in the delivery of the mixture to the ferrogram substrate.

5. The sample was again recapped and vigorously hand shaken. Five cc of the grease mixture was then transferred by pipet into another 1/2-ounce bottle. A ferrogram was then prepared from this mixture using Solvent #2 as a washer/fixer solution.

6. A microscopic examination was performed using these ferrograms to assess the wear/condition of each gearbox.

IV. TEST RESULTS AND DISCUSSION

A. GENERAL. Gearsets 7 and 8 (gearboxes 3 and 4) were tested at locations 3 and 4 respectively. Testing was suspended when 29,614,000 revolutions were recorded on the large gear. These gearsets successfully completed the desired time without failure. Optical examination revealed that the gears were worn and the surfaces were abraded with some smearing.

B. FERROGRAPHIC RESULTS

1. GEARSET 7, GEAR 3

a. Sample Location 1 (Tooth End of Gear 3 at Small Diameter). The analysis of samples taken at location 1 for each of the five time intervals is summarized in Table 1.

TABLE I

SUMMARY OF FERROGRAPHIC RESULTS FOR GEAR 3, TOOTH END AT SMALL DIAMETER (LOCATION 1)

SAMPLE PERIOD TIME INTERVAL (NO./HR)	WEAR (%/um) RUBBING	WEAR (%/um) FATIGUE	WEAR (%/um) LAMINAR	SPHERE WEAR (NO./um RANGE)	LARGE/ SMALL RATIO	SEVERITY OF WEAR
1/191	70/7	25/10	5/22	-	1:166	775.5
2/380	85/4	13/9	2/12	-	1:300	14.2
3/565	-	-	-	-	-	-
4/755	*	-	-	-	-	-
5/950	90/3	5/5	5/10	4/3-10	1:250	8.0

* Very small amount.

(1) Time Interval 1. The wear-in period at this sampling location was evident; wear-in particles were observed in considerable quantities. The ratio of large-to-small particles indicates a normal wear-in of the surfaces occurred. Some temper coloration was also noted which is associated with exposure to high temperatures.

(2) Time Interval 2. A very high rate of large-to-small particles was generated.

(3) Time Intervals 3 and 4. Microscopic examination of the samples was not possible due to a heavy grease accumulation blocking the entry deposit, and the unavailability of additional grease to make a new ferrogram. However, a very small amount of rubbing wear was observed at time interval 4.

(4) Time Interval 5. Rubbing wear particles increased and a moderate rate of large-to-small particles was generated. Again, as in time interval 1, slight temper coloration was noted. The presence of spheres was first observed here.

b. Sample Location 2 (Gear 3 Tooth Contact Surface). The particle types at this sampling location for the five time intervals are presented in Table 2, as taken from ferrographic analysis data:

TABLE 2

SUMMARY OF FERROGRAPHIC RESULTS OF GEAR 3, TOOTH CONTACT SURFACE (LOCATION 2)

SAMPLE PERIOD TIME INTERVAL (NO./HR)	WEAR (%/um) RUBBING	FATIGUE	LAMINAR	SPHERE WEAR (NO./um RANGE)	LARGE/ SMALL RATIO	SEVERITY OF WEAR
1/191	65/5	33/10	2/17	5/4	1:200	594.7
2/380	-	-	-	-	-	-
3/565	95/6	5/8	-	8/1-5	-	34.8
4/755*	-	-	-	-	-	-
5/950	SOME	-	-	FEW	-	-

* Very small amount.

(1) Time Interval 1. The wear-in period was indicated as the majority of the particles was rubbing wear. The ratio of large-to-small particles indicated a high rate of wear particles. Some temper coloration and spheres were also noted.

(2) Time Interval 2. Microscopic examination was not possible due to an insufficient amount of grease provided to perform an accurate analysis.

(3) Time Interval 3. The percent of rubbing wear increased, as did the number of spheres observed Some scuffing particles were observed. A number of pitted particles and black oxide particles which are indicative of high temperature were also noted.

(4) Time Interval 4. A very small amount of rubbing wear was observed, but a detailed microscopic examination could not be accomplished because the slide was covered with grease residue which blocked the entry deposit. Insufficient grease was provided to make a new ferrogram.

(5) Time Interval 5. Again, grease residue blocked the entry deposit, making it impossible to complete a detailed microscopic examination; however, some small rubbing wear particles, polymer, and spheres could be observed.

c. Sample Location 3 (Tooth End of Gear 3 at Large Diameter). The particle types at this sampling location for the five time intervals are presented in Table 3, as taken from ferrographic analysis data:

TABLE 3

SUMMARY OF FERROGRAPHIC RESULTS OF GEAR 3,
TOOTH END AT LARGE DIAMETER (LOCATION 3)

SAMPLE PERIOD TIME INTERVAL (NO./HR)	WEAR (%/um)			SPHERE WEAR (NO./μm RANGE)	LARGE/ SMALL RATIO	SEVERITY OF WEAR
	RUBBING	FATIGUE	LAMINAR			
1/191	75/4	20/9	5/15	1*/-	1:200	33.8
2/380	90/4	10/10	-	2/1-3	1:250	22.0
3/565	90/6	-	10/15	1/4	1:250	60.6
4/755	FEW	-	-	-	-	-
5/950	98/4	-	2/20	6*/3-6 3-6	1:300	4.2

* At entry.

(1) Time Interval 1. The wear-in period was evident as was the high rate of wear particles (1:200). Some temper coloration and some slightly oxidized particles were also observed.

(2) Time Intervals 2 and 3. Examination indicated the wear rate had stabilized and the majority of wear was rubbing. Pitting and temper coloration was noted at time interval 2, and oxidation was observed at both time intervals.

(3) Time Interval 4. Although a few rubbing wear particles were noted, a detailed analysis could not be accomplished because grease residue (green chunks) blocked the entry deposit and an insufficient amount of grease was provided to make a new ferrogram.

(4) Time Interval 5. Examination indicated a very high generation rate of large-to-small particles (1:300), but the particles were mostly rubbing wear. Spheres were also observed.

2. GEAR SET 7, PINION 3

a. Sample Location 1 (Tooth End of Pinion 3 at Small Diameter). The particle types at this sampling location for the five time intervals are presented in Table 4 as taken from ferrographic analysis data:

TABLE 4

SUMMARY OF FERROGRAPHIC RESULTS FOR PINION 3,
TOOTH END AT SMALL DIAMETER (LOCATION 1)

SAMPLE PERIOD TIME INTERVAL (NO./HR)	WEAR (%/um) RUBBING	FATIGUE	LAMINAR	SPHERE WEAR (NO./um RANGE)	LARGE/ SMALL RATIO	SEVERITY OF WEAR
1/191	-	-	-	-	-	-
2/380	-	-	-	-	-	-
3/565	-	-	-	-	-	-
4/755	-	-	-	-	-	-
5/950	95/5	5/7	-	-	-	229.3

(1) Time Intervals 1 through 4. The samples could not be analyzed due to insufficient amounts of grease provided to make ferrograms. Therefore, the wear-in period for this pinion could not be assessed

(2) Time Interval 5. Some scuffing wear and temper coloration were found in addition to the debris types contained in Table 4.

b. Sample Location 2 (Pinion 3, Tooth Contact Surface). The particle types at this sampling location for the five time intervals are presented in Table 5, as taken from ferrographic analysis data:

TABLE 5

SUMMARY OF FERROGRAPHIC RESULTS FOR PINION 3,
TOOTH CONTACT SURFACE (LOCATION 2)

SAMPLE PERIOD TIME INTERVAL (NO./HR)	WEAR (%/um) RUBBING	FATIGUE	LAMINAR	SPHERE WEAR (NO./μm RANGE)	LARGE/ SMALL RATIO	SEVERITY OF WEAR
1/191	85/4	15/10	-	-	1:300	478.7
2/380	95/5	5/7	-	6/1-4	1:250	7.9
3/565	85/5	5/12	-	10/2-9	1:250	3.4
4/755	-	-	-	-	-	-
5/950	-	-	-	-	-	-

(1) Time Interval 1. Most of the particles were rubbing wear indicating the wear-in period. The ratio of large-to-small particles (1:300) is an indication of a high rate of wear particles. Some slightly oxidized particles and temper coloration were also noted.

(2) Time Interval 2. The amount of rubbing wear increased and some spheres were observed. Temper coloration was again evident and some particles were pitted.

(3) Time Interval 3. Examination showed a decrease in rubbing wear but a definite percentage (10%) of spheres. The ratio of large-to-small particles seemed to have stabilized at 1:250. Some cutting wear and oxidized particles were presented.

(4) Time Intervals 4 and 5. Detailed analysis was not possible due to an insufficient amount of grease provided to make ferrograms. However, at time interval 3, very few wear metal particles were present.

c. Sampling Location 3 (Tooth End of Pinion 3 at Large Diameter). The particle types at this sampling location for the five time intervals are presented in Table 6, as taken from ferrographic analysis data:

TABLE 6

SUMMARY OF FERROGRAPHIC RESULTS FOR PINION 3, TOOTH END AT LARGE DIAMETER (LOCATION 3)

SAMPLE PERIOD TIME INTERVAL (NO./HR)	WEAR (%/μm)			SPHERE WEAR (NO./μm RANGE)	LARGE/ SMALL RATIO	SEVERITY OF WEAR
	RUBBING	FATIGUE	LAMINAR			
1/191	80/5	13/8	2/10	2%/2-5	1:200	412.8
2/380	-	-	-	-	-	-
3/565	-	-	-	-	-	-
4/755	95/4	5/25	-	FEW/2-5	1:300	264.4
5/950	SMALL AMOUNT	SMALL AMOUNT	-	-	-	-

(1) Time Interval 1. The wear-in period was evident as was the high rate of wear particles (1:200). Black oxide particles (3% of total) and some temper coloration were also observed

(2) Time Intervals 2 and 3. Microscopic analysis was not possible due to insufficient grease provided to make good ferrograms; however, green chunks were observed on the slide from time interval 3.

(3) Time Interval 4. Although the generation rate of large-to-small particles was very high, the particles were mostly rubbing. Some oxidation, temper coloration, and a few spheres were also noted.

(4) Time Interval 5. A detailed anlysis was not possible due to an insufficient amount of grease provided to make a ferrogram. However, some rubbing and fatigue particles as well as some temper coloration could be seen.

3. GEARSET 8 (GEAR 4)

a. Sample Location 1 (Tooth End of Gear 4 at Small Diameter). The particle types at this sampling location for the five time intervals are presented in Table 7, taken from ferrographic analysis data:

TABLE 7

SUMMARY OF FERROGRAPHIC RESULTS FOR GEAR 4, TOOTH END AT SMALL DIAMETER (LOCATION 1)

SAMPLE PERIOD TIME INTERVAL (NO./HR)	WEAR (%/µm) RUBBING	WEAR (%/µm) FATIGUE	WEAR (%/µm) LAMINAR	SPHERE WEAR (NO./µm RANGE)	LARGE/ SMALL RATIO	SEVERITY OF WEAR
1/191	-	-	-	-	-	-
2/380	-	-	-	-	-	-
3/565	-	-	-	-	-	-
4/755	95/5	5/6	-	-	1:350	499.0
5/950	90/4	5/5	5/12	-	1:250	202.0

(1) Time Intervals 1 and 2. The samples could not be analyzed due to insufficient amounts of grease provided to make ferrograms. Therefore, the wear-in period could not be assessed for this gear.

(2) Time Interval 3. Analysis could not be made because the slide was covered with grease residue and insufficient grease was left to make another slide.

(3) Time Interval 4. Some temper coloration was found and many particles were scored. The ratio of large-to-small particles indicated a high rate of wear particles.

(4) Time Interval 5. Some temper coloration could be seen. The ratio of large-to-small particles indicated a lower rate of wear particles.

b. Sample Location 2 (Gear 4, Tooth Contact Surface). The particle types at this sampling location for the five time intervals are presented in Table 8, as taken from ferrographic analysis data:

TABLE 8

SUMMARY OF FERROGRAPHIC RESULTS FOR GEAR 4, TOOTH CONTACT SURFACE (LOCATION 2)

SAMPLE PERIOD TIME INTERVAL (NO./HR)	WEAR (%/µm) RUBBING	WEAR (%/µm) FATIGUE	WEAR (%/µm) LAMINAR	SPHERE WEAR (NO./µm RANGE)	LARGE/ SMALL RATIO	SEVERITY OF WEAR
1/191	78/4	15/5	2/12	5%/1-5	1:300	333.0
2/380	95/3	5/4	-	-	-	9.6
3/565	-	-	-	-	-	-
4/755	-	-	-	-	-	-
5/950	94/4	3/5	3/20	1%/2-4	1:250	38.3

(1) Time Interval 1: Most of the particles were rubbing wear, indicating the wear-in period. The ratio of large-to-small particles (1:300) indicated a high rate of wear particles. Many particles had temper coloration. Many spheres were also observed

(2) Time Interval 2. The amount of rubbing wear particles increased.

(3) Time Intervals 3 and 4. Analysis could not be made due to insufficient amounts of grease provided to make ferrograms.

(4) Time Interval 5. The majority of particles were still rubbing wear. Some spheres could again be seen. The ratio of large-to-small particles (1:250) indicated a high generation rate of wear particles.

c. Sample Location 3 (Tooth End of Gear 4 at Large Diameter). The particle types at this sampling location for the five time intervals are presented in Table 9, as taken from ferrographic analysis data:

TABLE 9

SUMMARY OF FERROGRAPHIC RESULTS FOR GEAR 4, TOOTH END AT LARGE DIAMETER (LOCATION 3)

SAMPLE PERIOD TIME INTERVAL (NO./HR)	WEAR (%/µm) RUBBING	FATIGUE	LAMINAR	SPHERE WEAR (NO./µm RANGE)	LARGE/ SMALL RATIO	SEVERITY OF WEAR
1/191	75/5	20/8	3/10	2%/2-5	1:250	553.4
2/380	-	-	-	-	-	-
3/565	-	-	-	-	-	-
4/755	90/3	5/6	5/22	15/1-7	1:300	17.2
5/950	-	-	-	-	-	-

(1) Time Interval 1. The wear-in period was evident as was the high rate of wear particles (1:250). Some temper coloration was also observed.

(2) Time Intervals 2 and 3. Analysis could not be made due to insufficient amounts of grease provided to make ferrograms. At time interval 3, however, it could be seen that most of the particles were rubbing wear. Also present were some cutting wear and fatigue particles, black oxide particles, and some temper coloration.

(3) Time Interval 4. The large-to-small ratio indicated a high generation of wear rate particles, but the majority were rubbing wear. Some temper coloration was noted and some particles with striations could also be seen.

(4) Time Interval 5. Analysis was not possible due to an insufficient amount of grease provided to make a ferrogram.

4. Gearset 8 (Pinion 4)

a. Sample Location 1 (Tooth End of Pinion 4 at Small Diameter). The particle types at this sampling location for the five time intervals are presented in Table 10, taken from ferrographic analysis data:

TABLE 10

SUMMARY OF FERROGRAPHIC RESULTS FOR PINION 4, TOOTH END AT SMALL DIAMETER (LOCATION 1)

SAMPLE PERIOD TIME INTERVAL (NO./HR)	WEAR (%/um) RUBBING	FATIGUE	LAMINAR	SPHERE WEAR (NO./um RANGE)	LARGE/ SMALL RATIO	SEVERITY OF WEAR
1/191	90/-	10/-	-	-	1:300	1831.2
2/380	-	-	-	-	-	-
3/565	-	-	-	-	-	-
4/755	-	-	-	-	-	-
5/950	90/-	10/-	-	-	1:300	430.0

(1) Time Interval 1. A very high amount of wear particles was generated (1:300), but the majority were rubbing wear which is typical during the wear-in period. A fair amount of temper coloration was also observed.

(2) Time Interval 2. Detailed analysis could not be made due to heavy grease residue on the slide and an insufficient amount of grease remaining to make a good slide. However, the particles that could be seen appeared to be small rubbing wear particles.

(3) Time Intervals 3 and 4. Analysis could not be made due to insufficient amounts of grease provided to make ferrograms

(4) Time Interval 5. The generation rate of wear particles remained high, but the majority were rubbing wear. Some temper coloration was observed and most particles were pitted.

b. Sample Location 2 (Pinion 4, Tooth Contact Surface). The particle types at this sampling location for the five time intervals are presented in Table 11, as taken from ferrographic analysis data:

TABLE 11

SUMMARY OF FERROGRAPHIC RESULTS FOR PINION 4, TOOTH CONTACT SURFACE (LOCATION 2)

SAMPLE PERIOD TIME INTERVAL (NO./HR)	WEAR (%/µm) RUBBING	FATIGUE	LAMINAR	SPHERE WEAR (NO./µm RANGE)	LARGE/ SMALL RATIO	SEVERITY OF WEAR
1/191	80/5	15/8	5/15	1/4	1:250	825.4
2/380	85/5	5/5	-	1/2	-	43.2
3/565	95/2	5/5	-	SOME/3-5'	1:300	278.2
4/755	-	-	-	-	-	-
5/950	95/5	5/3	-	1/1-3	1:300	19.3

(1) Time Interval 1. A high amount of wear particles was generated but most were rubbing wear, typical of the wear-in period. Some temper coloration and one sphere were also observed.

(2) Time Interval 2. Most of the particles continue to be rubbing wear. In addition, 10% of the total particles were oxide; moderate temper coloration and one sphere were observed

(3) Time Interval 3. Analysis indicated a higher generation rate of wear particles (1:300) but the majority were still rubbing wear. However, the rubbing wear was smaller than in previous samples. One piece of cutting wear and several spheres were noted.

(4) Time Interval 4. Analysis could not be made due to an insufficient amount of grease provided to make a ferrogram.

(5) Time Interval 5. Analysis indicated continued very high generation rate of wear particles (1:300), with the majority of particles being rubbing wear. One sphere was noted

c. Sample Location 3 (Tooth End of Pinion 4 at Large Diameter). The particle types at this sampling location for the five time intervals are presented in Table 12, as taken from ferrographic analysis data:

TABLE 12

SUMMARY OF FERROGRAPHIC RESULTS FOR PINION 4, TOOTH END AT LARGE DIAMETER (LOCATION 3)

SAMPLE PERIOD TIME INTERVAL (NO./HR)	WEAR (%/µm)			SPHERE WEAR (NO./µm RANGE)	LARGE/ SMALL RATIO	SEVERITY OF WEAR
	RUBBING	FATIGUE	LAMINAR			
1/191	90/4	10/6	-	-	-	164.6
2/380	-	-	-	2/2-7	-	-
3/565	-	-	-	FEW/3-11	-	-
4/755	98/4	-	2/7	-	1:350	108.3
5/950	95/4	5/6	-	-	1:300	215.1

(1) Time Interval 1. The majority of wear particles were rubbing wear. It was also observed that some particles were slightly oxidized.

(2) Time Interval 2. A detailed analysis could not be made due to an insufficient amount of grease provided to make a ferrogram. However, what could be seen on the slide appeared to be mostly rubbing wear. Two spheres were observed. as well as some oxidation.

(3) Time Interval 3. A detailed analysis could not be made, again, due to an insufficient amount of grease provided to make a slide. The particles that could be seen appeared to be from the wearing-off of machined surfaces. Some temper coloration could be seen, as well as a few spheres at the entry deposit.

(4) Time Interval 4. A very high generation rate of wear particles was evident. However, the majority were small rubbing wear particles. Some temper coloration was observed and many particles with striations were present.

(5) Time Interval 5. The generation rate of wear particles was still high, but again, the majority of particles were rubbing wear. Some temper coloration was also observed.

V. CONCLUSIONS

A. The testing of gearboxes 3 and 4, was terminated for time-up. The condition of the gears noted at that time was that the gears were worn and the surface was abraded with some smearing.

B. The analysis of the grease samples did not indicate a failure was occurring, which correlates with the gear condition. However, the only indication of the abraded condition observed during this analysis was the presence of some cutting wear at sampling location 2 (tooth contact surface) of both pinions 3 and 4, and at sampling location 3 (tooth end at large diameter) of gear 4. The cutting wear was not an overall wear type present on the slide, but only a very small percentage of wear type. For this reason, it could not be stated that the cutting wear, as noted, was characteristic to the gear condition. Possibly, more indication of this condition could have been observed at the sampling locations that were not analyzed due to heavy grease residue on the slide and/or an insufficient amount of grease available to make a usable ferrogram.

C. Based on the data that was available. correlation could not be made between the assessment of gear conditions made at SKF and the analysis of ferrographic data performed at NAVAIRENGCEN on grease samples from spur gears.

D. In view of the fact that representative samples could not be obtained. the monitoring of the wear content of samples from grease-lubricated components is not practical as a maintenance tool.

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