

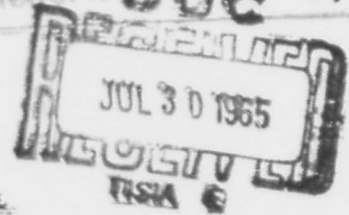
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STUDY OF HELICOPTER GEAR LUBRICATION

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STUDY OF HELICOPTER GEAR LUBRICATION

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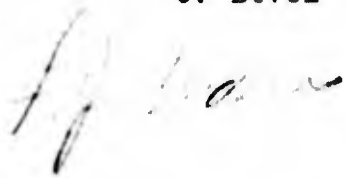
Bureau of Naval Weapons  
Washington, D.C.

Contract NOW 65-0323-c

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## STUDY OF HELICOPTER GEAR LUBRICATION

### Summary

Work carried out during the first quarter of Contract NOW 65-0323-c between Shell Oil Company and the U.S. Navy is discussed in this report. Two main subjects are treated: the first is the effect of several gear surface precoatings on gear performance; the second is the gear performance of a typical synthetic, tetraester, five-centistoke base oil.

It was found that precoating gears by heating in atmospheres of air, or a diester base oil, had little effect on the score load of a MIL-L-23699 test oil, while gears treated in a nitrogen atmosphere gave an increase in score load. Fatigue life as measured by the time to pitting failure, on the other hand, was considerably affected by the precoatings, particularly at high speed. In constant load tests at 6400 rpm it was found that the diester oil precoating extended gear life by a factor greater than seven, while the air precoating increased life three times. Under these same conditions the nitrogen treatment had no effect on gear life. While the coating techniques investigated represent only an initial attempt in this field, the improvement in performance is sufficient to warrant further study.

From tests with the synthetic base oil, it was found that this oil is rather insensitive to break-in, and that fatigue failures occurred by fatigue-scoring rather than by pitting. The purpose of these tests was to develop groundwork for future exploratory studies involving the effects of EP additives on gear performance.

### Introduction

In recent discussions with personnel of a major manufacturer of helicopters it was again confirmed that the leading cause of transmission failure, and thus the factor limiting transmission overhaul life, was fatigue pitting of the slow-speed planetary stage gear teeth. The present work is primarily concerned with the causes and possible alleviation of gear tooth pitting.

The main channels of the research effort are: 1) the exploration of the character of the break-in response of gears, and 2) the investigation of the causes of differences in pitting performance between pertinent lubricants in terms of their physical and chemical properties. When the nature of these two parameters is better understood, our objective will then be to define the limits of performance improvements which may be reasonably expected in practical systems. In the present work, exploratory studies of several surface-modifying coatings which could affect break-in and alleviate fatigue effects have been carried out.

Considerable information is available in the literature concerning lubricant films, their formation, thickness, strength, and chemical composition, but less is known about the behavior of preformed films or precoatings, i.e., films formed on the metal surfaces before they are actively brought into contact. Fitzsimmons and Zisman<sup>1</sup> have reported on coatings of polytetrafluoroethylene as lubricants and preservatives, and Rounds<sup>2</sup> has shown that

some precoatings can considerably increase fatigue life in a four-ball machine. Notable among these was an increase in life by a factor of 23 by heating the test balls in a diester oil. Heating in air was shown to decrease life markedly, by a factor of five. More recently, Waterhouse and Allery<sup>3</sup> have shown that by proper treatment, Parco-Lubrited coatings can significantly increase fretting fatigue life. Further, in studies conducted at the U. S. Naval Research Laboratory it has been found that the life of ball bearings can be significantly extended by application of a thin fluoropolymer film.<sup>4</sup>

In accordance with the above objectives we have examined some of the more promising precoatings for any possible benefit relative to useful life of gears under conditions that normally lead to failure by fatigue pitting. In addition, a base tetraester oil consisting of a mixture commercially available synthetic tetra- and hexa-esters was evaluated to produce baseline data for future EP additive studies. This report describes the results of these tests.

### Test Equipment and Procedures

A detailed description of the testing equipment and the procedures employed will not be given here, since both have been fully described previously.<sup>5</sup> A brief description at this point is in order, however, to promote clear understanding and orientation of thought.

Gear tests were performed on a high-speed spur-gear testing machine. The design of the test gear and power gear trains permits loading and unloading the test gears at operating speeds. In this work the test gears were always brought up to operating speed before load was applied. The mechanics of the loading system are such that one pound of "scale" load is equivalent to 17.7 pounds of actual tooth load transmitted along the line of action.

The following data apply to the test gears, which are precision manufactured to extremely close tolerances:

Tooth Form	Involute - No Tip Relief or Undercut
Number of Teeth, Pinion	17
Number of Teeth, Gear	19
Diametral Pitch	6
Pressure Angle, Degrees	20
Face Width, Inches	0.25
Center Distance, Inches	3.000
Material	SAE 3312 or Equivalent Steel
Hardness of Working Surface, Rc	60-62
Depth of Case Hardness, Inches	0.025 to 0.040
Surface Finish of Working Surface, Microinch, RMS	20

Although the gear width as shown above is 0.25 inch, in actual operation they are offset so that contact occurs on only 0.10 inch of face width. This is done for several reasons. It permits higher contact stress for a given applied load, doubles the number of tests possible on one set of gears, and provides an unworn track in the middle of each tooth surface which permits comparison with worn areas.

Before being tested the gears are checked for profile accuracy, tooth spacing, eccentricity, surface finish, and hardness. They are weighed before and after each test, and are cleaned ultrasonically with a solvent prior to testing.

The test oil is pumped from a sump through electrically heated piping and a flow control jet at the point of incoming mesh, and returns by gravity from the gear box to the sump. The test oil flow rate was nominally 10 ml/sec and the temperature was kept at 100°F at the jet. The capacity of the system is approximately one quart, to permit testing of small samples.

Three types of tests were employed in this work, and these differ only in the load-time schedule followed.

The load-carrying capacity (LCC) test determines the maximum load the gears will tolerate at a given speed when operated under a schedule of increasing scale-load increments of 4 lb (70.8-lb transmitted load) for 5 minutes each. The load at failure under these conditions is termed the "score load" of the oil at the particular speed of operation.

In the second type of test the gears are operated at constant load (CL) at a given speed until failure occurs. This test is intended to accelerate and point up any fatigue effects. It will be noted that the difference between the score load of an oil as defined by the LCC test and the highest constant load the gears will tolerate without immediate failure is an indication of the break-in sensitivity of that oil, since in one case there is an inherent break-in and in the other there is none.

The third type of test is the break-in (BI) test, in which the load-time schedule can be varied to produce any degree of break-in severity desired. This test furnishes data supplementary to the LCC and CL tests and provides information on optimum break-in procedures.

At various intervals throughout each of the tests microscopic inspections of both the gear and pinion teeth are made in order to follow closely and assess the deterioration of the working surfaces.

#### Preparation of Surface Precoatings

Three different surface treatments were applied to the gears before testing, these being coatings obtained with a diester base oil, air, and nitrogen. In each case the technique was the same: the gears were immersed in the coating medium and heated in an oven at 400°F for a period of 20 hours. This particular technique has been found in the case of the diester coating to provide optimum fatigue life.<sup>2</sup>

The diester oil precoatng consisted of immersing the gears in a beaker containing the base oil, di-2-ethyl hexyl sebecate, with spacers between the gears to assure complete contact of the oil with the gear teeth. After treatment the gear appearance had changed from shiny to a light-brown varnish-type deposit. The gears were allowed to cool to room temperature while immersed in the diester oil.

In a second treatment a new set of test gears was heated in the oven with no attempt being made to exclude or control moisture, and as indicated by the rusty red appearance after heating, a thin layer of iron oxide had been formed. These gears were cooled by immersing in the test oil at room temperature.

In order to minimize effects of oxides and yet at the same time subject the gears to all the other effects of the heating process a third treatment, consisting of heating in an inert atmosphere of nitrogen, was performed. The gears were placed in the oven, separated by spacers, and covered with an inverted beaker. Nitrogen was bled into the beaker during the heating period in order to displace any oxygen. At the end of the treating period the gears were cooled in a nitrogen atmosphere to room temperature. The bright blue appearance of the gears after treatment suggested that this coating was of a different chemical composition than the air-formed coating.

It should be mentioned that in performing the above surface treatments additional changes in the gears were at the same time taking place. Hardness, for example, in all three cases was lowered an average of 2.5 Rc units, from 60.5 to 58.0 Rc. No attempt was made to restore the gears to their original hardness. Other changes were undoubtedly brought about, such as some stress relief, and metallurgical changes, and these were assumed to be the same regardless of the type of treatment.

### Spur-Gear Test Results

#### Effect of Surface Precoatings

The test oil employed in the work on surface coatings was the same five-centistoke oil as reported in Reference 6, viz., MIL-L-23699 (A). Results of tests run under two different load-time schedules, one a standard LCC schedule and the other a break-in schedule, are shown in Table 1. The latter schedule has been shown previously to be particularly severe with uncoated gears because fatigue occurs initially without benefit of surface polishing.

As shown in Table 1, neither the diester oil nor the air precoating had any significant effect on the score load of MIL-L-23699 (A) oil at a pinion speed of 6400 rpm. With the nitrogen precoating, on the other hand, the somewhat higher score load of 850 lb was obtained. This result is not totally unexpected. Parallel data have been obtained by Ku and Baber,<sup>7</sup> who showed that scuff-limited loads in a Ryder gear machine can be increased by surrounding the test gears with an atmosphere of nitrogen.

The last column of Table 1 shows results obtained from the break-in tests. With each precoating, significant improvement in load-carrying capacity relative to that of the uncoated gears was obtained. As will be discussed later, most, but not all, of this improvement can be attributed to the beneficial effects of the precoatings.

Table 2 shows effects of the precoatings on constant-load gear life at pinion speeds of 1600 rpm and 6400 rpm. It should be noted here that transmitted loads imposed on the gears at the two speeds are different, being 637 lb at 1600 rpm and 354 lb at 6400 rpm. In each case, these loads were found previously to be the highest constant loads the gears can tolerate without immediate failure,<sup>6</sup> and they were employed here in order to shorten testing time.

As shown in the table, there is a considerable influence of the pre-coatings on fatigue life of the gears. At 6400 rpm, the diester base oil and air precoatings improved gear life by factors of 7+ and 3, respectively, while the nitrogen treatment was ineffective. At 1600 rpm the results are in the same order as at the higher speed, but the observed effect of pretreating is not as large. Based on previous experiments relating transmitted load to gear life (cf. Figure 6, Reference 6), the above reduction in sensitivity (to pre-coatings at 1600 rpm) is attributed to the higher load employed, rather than to a speed effect. As noted in the table, all failures were by pitting in the area of the pinion pitch line or dedenda except in the case of the uncoated gears at 6400 rpm, in which failure was due to fatigue-scoring.

#### Performance of Tetraester Base Stock

As mentioned previously, the tests on the tetraester base stock were performed to prepare the way for future experiments which involve the effects of EP additives on gear performance. For this reason, the data are presented here for purposes of record only and will be followed by related studies.

Results of LCC and BI tests at 6400-rpm pinion speed on the oil, designated WRNC-1, are shown in a load vs time plot in Figure 1. Two LCC tests resulted in scoring of the pinion addenda at a transmitted load of 354 lb. In a BI test, a standard LCC load schedule was followed to within one load step of the score load, at which point this load (283 lb) was held until failure occurred by (fatigue) scoring of the pinion addenda, after a total operating time of 50 minutes. In a second BI test, a load vs time schedule with load increments half those of the LCC schedule was followed. Failure under these conditions occurred, again by pinion addenda scoring, at a 319-lb transmitted load.

Two CL tests were run on WRNC-1. The results are shown plotted on a load vs log time schedule in Figure 2. In the first test the gears were run one load step under the score load, at 283 lb. Fatigue-scoring of the pinion addenda occurred after 25 minutes of operation. In the second test, at 212-lb transmitted load, failure occurred via the same mechanism after 270 minutes of operation. The line connecting the two points in the figure illustrates the typical increase in life with decreasing load, the slope corresponding to a doubling of gear life with a decrease in transmitted load of about 20 lb. It will be recalled that this is the same slope as found previously for two MIL-L-23699 oils and a MIL-L-7808 oil.<sup>6</sup>

#### Discussion and Conclusions

The surface coatings reported herein, while certainly representing only a small part of known precoatings, have shown sufficient increase in the fatigue life of our test gears to warrant further study.

It has been shown in Table 1 that under LCC conditions surface coatings, except in the case of the nitrogen-treated gears, had no significant effect on score load, while under the break-in conditions all three sets of treated gears gave appreciable improvement in failure load. As discussed previously, the

low failure load with the untreated gears in the break-in tests is attributed to the accumulation of fatigue cycles without corresponding beneficial surface polishing.<sup>6</sup> The improvement shown for the coated gears in the break-in tests may be due to accelerated surface modifications, such as polishing out geometric imperfections, or the benefit may stem from some unidentified mechanism of either stress reduction or an increase in the fatigue resistance of the gear-lubricant system.

The effect on load-carrying capacity that can be attributed to softening of the gear metal during the coating treatment can be estimated from the work of Borsoff.<sup>8</sup> From his data it is estimated that a decrease in Rockwell C hardness of 2.5 units in the range 55-62 Rc will give an increase in score load of slightly more than 3-lb scale load (53-lb transmitted load). This is just a little less than the range of repeatability of the test, indicating the effect of a 2.5 Rc change could be seen only on a statistical basis. Further, it will be noted that this expected effect represents only a small part of the total improvement shown in failure loads in the BI tests.

The effect of a change in hardness on the fatigue life of gears is somewhat more difficult to estimate. Carter, et al,<sup>9</sup> and Baughman<sup>10</sup> have shown an increase in rolling-contact fatigue life with increasing hardness at elevated loads. If the effect is in the same direction in the present gear tests, then the treated gears would be handicapped with respect to fatigue life, and the improvements in life attributable to precoating would be greater than those shown in Table 2. Again, however, this effect is expected to be small over a 2.5 Rc interval.

The amount of improvement in gear life afforded by a simple diester base-oil precoating has been shown to be from almost 2 to more than 7 times that of the untreated gears, depending upon operating conditions. In this regard it should be mentioned that in the CL test with the diester-coated gears at 6400 rpm (Table 2) although no fatigue pitting occurred on the test gears, considerable wear of an unusual nature had taken place on the pinion addenda. This is described below and shown by the photographs in Figure 3 for purposes of record.

The two pictures in Figure 3 are of the same diester-treated pinion tooth after  $768 \times 10^3$  cycles of operation at 6400 rpm and 354-lb transmitted load. The only difference between the two pictures is the position of the light during photographing. In the left-hand picture it appears as if the entire worn area in the addendum is scored, whereas the other picture shows that scoring has occurred only on a small portion of the addendum, near the tip of the tooth. What appears to be scoring in the one picture is actually fairly deep, irregular, abrasion as shown in the right-hand picture by the light reflected off the surface. The true nature of this type of wear has not been isolated, although it apparently is not severe enough to cause catastrophic gear failure. Both photographs show several small surface cracks in the dedendum. These did not increase appreciably in size up to the time the test was stopped at  $2668 \times 10^3$  cycles.

A further observation from Table 2 is that, contrary to the findings of Rounds,<sup>2</sup> in our tests precoating with air improved fatigue life. The appearance of the gears after treatment suggests that a polishing action due to the surface oxides was in operation, accelerating break-in.

From the data obtained in tests with tetraester base oil, WRNC-1, it is apparent that the oil is not sensitive to break-in. Failures for LCC, CL, and BI tests were within one load step of each other. A further observation is that the oil exhibits a propensity for failure via the fatigue-scoring route. However, this is most likely due to an effect which has been observed previously, i.e., at loads near the score load, scoring is to be expected, while at lower loads pitting will occur.

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Table 1  
Effect of Various Precoatings On  
Transmitted Load at Failure for MIL-L-23699 (A)  
Oil at a Pinion Speed of 6400 rpm

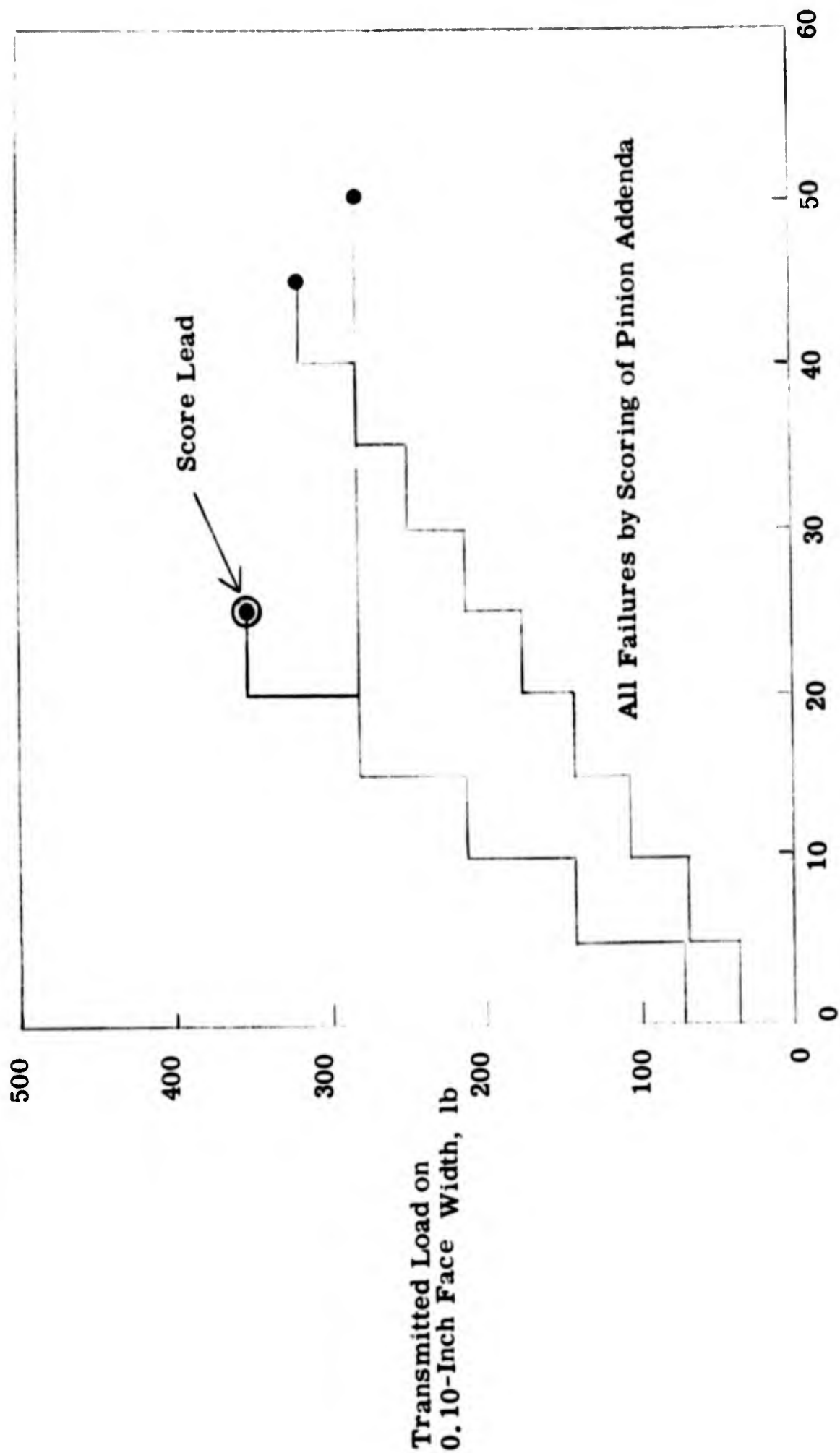
<u>Coating on Test Gears</u>	<u>Gear Color</u> <u>Before Test</u>	Score Load <sup>a</sup> From LCC Tests, <u>lb</u>	Failure Load <sup>a, b</sup> From BI Tests, <u>lb</u>
None	Shiny	637	212
Heated 20 Hr at 400°F in:			
Diester Base Oil	Light Brown	708	708
Air	Rusty Red	637	567
Nitrogen	Bright Blue	850	708

- a. All failures due to scoring of the pinion addenda.  
b. Load vs time schedule was the same as in the LCC test except that the transmitted load in the second time interval was 354 lb instead of 142 lb (See Figure 10b, Reference 6.).

Table 2  
Effect of Various Precoatings On  
Constant Load Gear Life with MIL-L-23699 (A)  
Oil At Two Speeds

<u>Coating on Test Gears</u>	<u>Gear Color Before Test</u>	<u>CL Life,<sup>a</sup> No. of Cycles x 10<sup>-3</sup></u>	
		<u>At 1600 rpm, 637 lb Load</u>	<u>At 6400 rpm, 354 lb Load</u>
None	Shiny	192	384 <sup>b</sup>
Heated 20 Hr at 400°F in:			
Diester Base Oil	Light Brown	336	>2688 <sup>c</sup>
Air	Rusty Red	288	1152
Nitrogen	Bright Blue	216	384

- a. All failures by pitting of pinion pitch line/dedenda except as noted.
- b. Failure by fatigue-scoring.
- c. No failure.



Time, Minutes

**Figure 1. GEAR TEST RESULTS ON WRNC-1  
AT A PINION SPEED OF 6400 RPM**

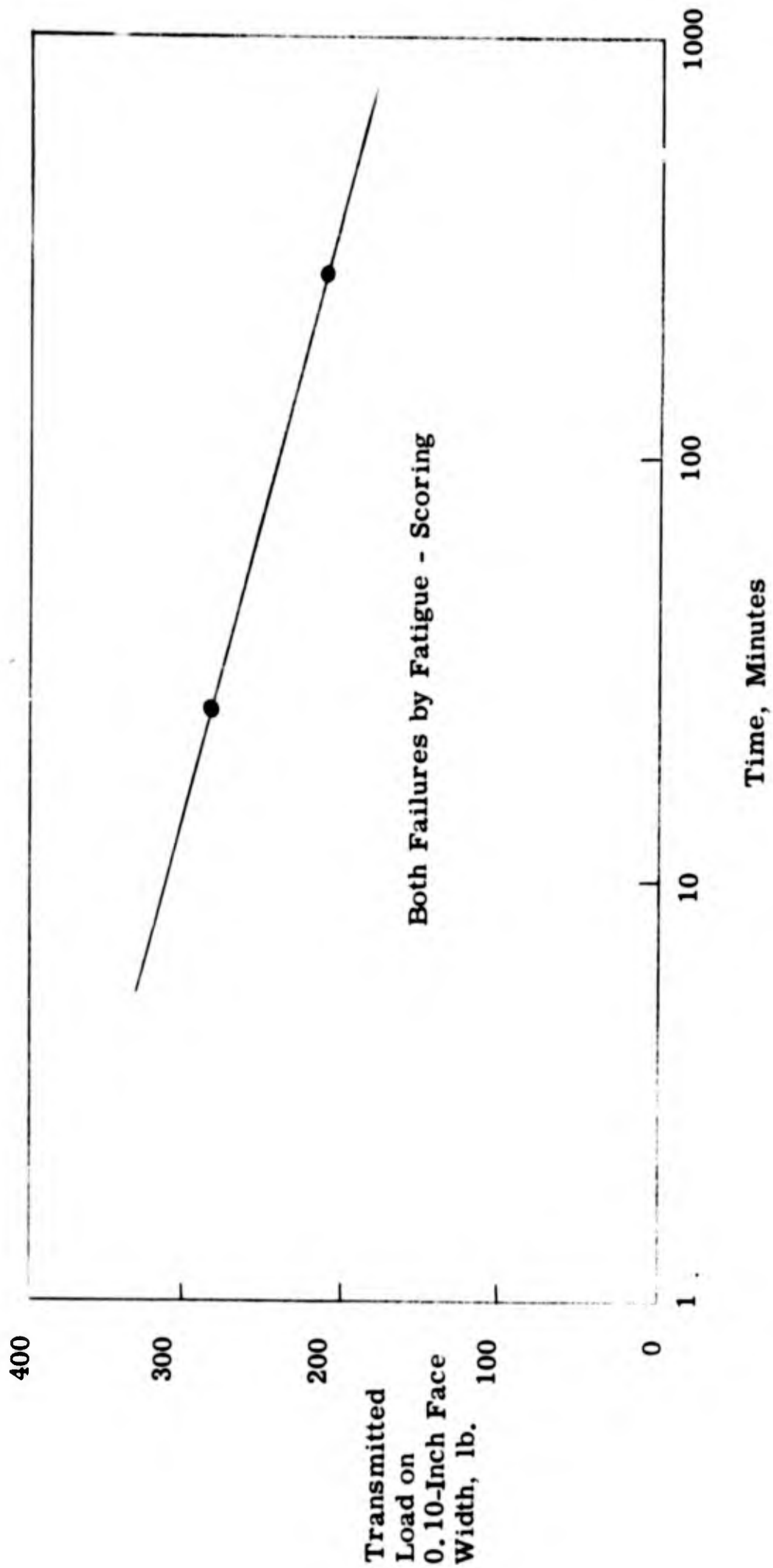


Figure 2. CONSTANT LOAD LIFE OF SPUR GEARS WITH WRNC-1 AT A PINION SPEED OF 6400 RPM

Figure 3. DIESTER OIL-COATED PINION TOOTH AFTER  $768 \times 10^3$  CYCLES  
AT 354-LB TRANSMITTED LOAD. MIL-L-23699(A) OIL AT 6400 RPM.

Note change in appearance of addendum as affected by light position.

