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ROLLING CONTACT FATIGUE OF SILICON NITRIDE

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13. ABSTRACT

Rolling contact fatigue studies were conducted comparing hot-pressed silicon nitride and consumable vacuum melted M-50 steel. Test results showed that:

a. Silicon nitride is superior to M-50 steel by at least an order of magnitude.

b. Surface finishing process significantly effects the fatigue life of silicon nitride.

c. Silicon nitride run in contact with M-50 steel may have a detrimental effect on the fatigue life of M-50 steel.

d. Skidding may be detrimental to the surface durability of silicon nitride.

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INTRODUCTION.

1. Over the past decade, the trend in turbine engine design (i.e. higher thrust-to-weight ratios) has required that mainshaft engine bearings operate at ever increasing DN (bearing bore in MM x RPM) conditions. It is estimated that by 1980 engine design will require rolling element bearing operation to 3.0×10^6 DN. Engines currently in the final stages of development, such as the F401 and the T700, require bearing operation to 2.2 million DN. Both ball and roller bearings are now speed limited to less than 2.5 million DN. This limitation in ball thrust bearings is mainly due to the reduction in fatigue reliability resulting from high centrifugal loading of the steel rolling elements. In addition, at higher speeds the magnitude of the ball bearing pre-load necessary to prevent skidding increases thereby further reducing fatigue endurance life.

2. Hot pressed silicon nitride (Si_3N_4) is a ceramic material, which because of its high flexure strength, has potentially wide applicability in advanced gas turbine engines. Since silicon nitride has a density of about 40 percent of the density of steel, one can expect a significant reduction in centrifugal loading from rolling elements made of silicon nitride. The weight reduction will also decrease the mass moment of inertia of the rolling element thereby reducing the pre-load necessary to prevent bearing failure due to skidding. Therefore, an advance in the state-of-the-art of bearing technology can be achieved with the use of bearings having conventional M-50 steel rings fitted with silicon nitride rolling elements. Since the reliability of bearings are measured by contact fatigue endurance life, it is necessary to characterize the fatigue life of silicon nitride and compare it to that of presently used vacuum melted M-50 steel over a wide range of stress levels, lubrication and temperature conditions. It is also necessary to characterize the type of surface damage which occurs under various conditions of rolling with sliding. Such conditions are expected to occur during bearing skidding and roller end loading.

3. Another application for silicon nitride is its use as a full bearing material in Expendable Turbine Engines (ETE) where the bearing temperatures (700°F or more) are beyond the capability of current bearing steels. In addition, the requirement for long shelf life without corrosion or brinelling is a further incentive for the use of ceramic bearing material in ETE's.

4. The purpose of this report is to document work accomplished to date with respect to the rolling contact fatigue characteristics of silicon nitride and to corroborate as well as compliment work conducted under contract to the Naval Air Systems Command (NAVAIR) which is reported in references (a) and (b).

5. The work performed by the Naval Air Propulsion Test Center (NAPTC) was authorized by NAVAIR AIRTASK Number A3200000/052B/4F4540000 of 1 June 1973.

CONCLUSIONS.

6. Silicon nitride, unlike other ceramic materials,produces rolling contact fatigue spalls similar to those found in hardened bearing steels. Unlike steel, however, the spalls appear to originate from cracking at the edge of the contact area of the silicon nitride test rods.

7. The rolling contact fatigue life of hot pressed silicon nitride (designated Noralide NC132) is superior to presently used engine bearing steel (consumable vacuum melted M-50 steel) by at least an order of magnitude.

8. The surface finishing process has a very significant effect on the fatigue life of silicon nitride.

9. Limited data obtained in this program indicate:

a. Silicon nitride when run against M-50 steel has a detrimental effect on the fatigue life of M-50 steel. This effect increases in severity with increasing temperature.

b. Skidding or sliding is detrimental to the surface durability of silicon nitride.

RECOMMENDATIONS.

10. The surface durability of silicon nitride in contact with itself and steel materials be throughly investigated at several temperature and load levels under rolling/sliding conditions.

DESCRIPTION OF MATERIALS.

Test Equipment -

11. All testing was conducted on the Rolling Contact (RC) Fatigue Machine, Alcor Model RC-30 modified to operate at elevated temperatures. This machine provides a simple and economical means of generating fatigue spalls similar to those found in full scale bearings(reference (c)). An overall view of the test set-up and a close-up of the test section are shown in Figures 1 and 2, respectively. A cylindrical test rod, three inches long by 0.375 inches in diameter is mounted in a precision chuck. A small electric motor drives the test rod, which in turn drives two hemispherically ground M-50 steel loading disks (or rollers). The disks are between 7.0 and 8.0 inches in diameter (regrinding disks for re-use changes their diameter) and have a crown radius of 0.25 inches. The load is applied by closing the disks against the test rod by using a micrometer-

threaded turnbuckle in series with a calibrated load cell. Lubrication is achieved by means of a drip feed system. A needle valve is used to control flow at a constant rate. The lubricant is heated by means of resistance heating wire wrapped around the drip tube. The lubricant temperature at the outlet of the drip tube is measured by a thermacouple and controlled by an "on-off" type temperature controller connected to the resistance coil. The test rod is heated by means of an induction coil. The temperature at the test track or contact area is measured by an infra-red sensing unit and is controlled by the temperature controller. The heating and temperature sensing system for the test rod is shown schematically in Figure 3. The end of the silicon nitride test rod is inserted into a steel collet for heating, because silicon nitride is not magnetic and cannot be heated inductively. The collet is inductively heated after which the heat is conducted to the test track. The test track temperature was calibrated as described in Appendix 1.

12. An acceleration type vibration pickup is mounted on one of the support yokes. This instrument acts as a failure sensor and terminates the test immediately upon occurrence of a fatigue failure. The number of stress cycles to failure is recorded on a mechanical cycle counter which is connected to the drive shaft through a 100 to 1 gear reduction. After a test has been terminated, several additional test runs can be made on one test rod by moving the rod axially to a fresh test surface.

Test Specimens and Lubricant -

13. The silicon nitride test rods used in this program were obtained from Norton Company and were made of two silicon nitride materials designated as HS110 and NC132. The NC132 evolved from the HS110 and represents an improvement in flexure strength as a result of having a more homogeneous microstructure, a reduction in the number of inclusions and increased density (i.e. less porosity). The test rods referred to in this report are listed in Table 1 with pertinent information. The surface finish processing of one (designated rod number 11) of the HS110 rods was different form the remainder as shown in Table 1. In addition to being tested at NAPTC, test rod number FM6 was previously tested by the Norton Company and reported in reference (a). Although test rod number 11 was not reported in reference (a), the results from another test rod (designated number 12) which was made from the same billet of material and finish processed in exactly the same way as rod number 11, was reported in reference (a). Test rods designated 73-22 and 73-23 were previously tested at the Norton Company and the results reported in reference (b). The fatigue reliability of silicon nitride rods tested at NAPTC was compared against that of consumable vaccum melted M-50 steel test rods hardened to 62-64 Rockwell.C. This is a commonly used bearing steel in gas turbine engines and therefore makes an ideal baseline material for comparison. The surface finish of both the M-50 steel and the silicon nitride were in the range of 4 to 8 microinches RMS.

14. The lubricant used in all the testing was Hercolube A, a commonly used base oil for blending lubricants conforming to Military Specification MIL-L-23699B.

METHOD OF TEST.

15. The test conditions were as follows:

a. Oil temperature - 350°F.

b. Test rod temperature - ambient and 500°F.

c. Rotating speed - 12500 and 5000 RPM.

d. Applied load - 220 to 490 pounds.

e. Lubrication - 20 drops/minute - (single pass)

16. A track location on a test specimen was run until one of the following occurred:

a. Failure of the test rod.

b. Failure of the loading disks.

c. Termination of test because it did not sustain a failure after running to a pre-determined number of stress cycles.

The number of stress cycles was recorded as a data point for each test. Typical fatigue spalls for M-50 steel and silicon nitride are compared in the photomicrographs in Figure 4.

Contact Stresses -

17. The endurance life of steel bearing surfaces is inversely proportional to the ninth power of the maximum Hertz contact stress. Because silicon nitride has an elastic modulus much higher than steel (45×10^6 psi for silicon nitride vs 30×10^6 psi for steel), the silicon nitride in contact with steel will produce a higher stress than steel contacting steel for the same applied load. Therefore, in comparing results between silicon nitride and M-50 steel at a given contact stress, this load difference should be borne in mind. Figure 5 graphically shows the relationship of maximum Hertz stress vs load for the two materials on the RC rig configuration. The calculations are based on reference (d). The calculations have been checked against those reported by the Norton Company and found to be in agreement.

Data Analysis -

18. For the steel and the number 11 silicon nitride test specimen, a

series of tests were performed in order to attempt to make up a sample size or group of data sufficiently large to reliably estimate, by appropriate statistical methods, the various population life (or endurance) parameters. The data were assumed to be distributed as a Weibull function, which is a population probability distribution that appears to fit contact fatigue data very well (reference (e)). Plots on special Weibull probability paper and a least squares regression analysis were performed in order to fit a straight line through the data. In addition, 90 percent confidence intervals are also calculated according to the method of reference (e). A typical Weibull plot is shown in Figure 6. The plot shows an estimate of the cumulative percentage failed vs stress cycles to failure. The dashed line shown in Figure 6 which is perpendicular to the Weibull line and passes through the estimation point, is used to determine nomographically the slope of the Weibull line and the percentage level where the mean life occurs. A computer program was developed in order to make the analysis. Several important distribution parameters which are used for comparison between groups were calculated. They are the L_{10} life, L_{50} life, L_m life and the Weibull slope (β). These are defined as follows:

a. L_{10} life - The number of stress cycles exceeded by 90 percent of the population (Figure 6).

b. L_{50} life - The number of stress cycles exceeded by 50 percent of the population (Figure 6).

c. L_m life - Means life of the population (Figure 6).

d. Weibull slope (β) - The slope of the computed Weibull line. This parameter indicates the amount of scatter in the data (Figure 6).

19. The NC132 silicon nitride test specimens did not produce enough failures (only two) to be evaluated statistically as described in the previous paragraph. The actual number of stress cycles accumulated was used for comparison against the M-50 steel specimen.

ANALYSIS OF RESULTS AND DISCUSSION.

Fatigue Test Results -

20. The test result generated at NAPTC, at ambient test rod temperature, on silicon nitride and M-50 steel are given in Table II. The NC132 was run at two Hertz stress levels, namely 800,000 psi and 900,000 psi. The M-50 steel and the HS110 silicon nitride were run at both 700,000 psi and 800,000 psi. Data for M-50 steel could not be generated at 900,000 psi because of load cell limitations.

21. Comparison of M-50 steel and silicon nitride NC132 data taken from Table II at the 800,000 psi Hertz stress level are shown graphically in Figure 7. No failures were obtained with NC132 silicon nitride even though some tests were run to an extremely large number of stress cycles. In one case 344.6 million stress cycles were accumulated without failure. Tests of this duration are more than an order of magnitude times the average life of the M-50 steel at the same stress or load level.

22. Two failures were obtained on NC132 silicon nitride at the 900,000 psi Hertz stress level. The time to failure of each run was about seven times the mean life of M-50 steel when tested at 800,000 psi Hertz stress as shown in Table II.

23. Test rod number 11 (HS110 material with different finish processing) incurred a failure on all runs made while FM6 (another HS110 material) did not incur any failures. The fatigue life of rod number 11 was inferior to the vacuum melt M-50 and FM6 as shown in Table II, indicating that surface finish processing has a significant effect on fatigue life. The surface appearance of rod number 11 when examined microscopically appeared pitted in the unrun area as discussed later under sub-section entitled "Examination of Wear Tracks".

24. Contrary to NAPTC results, testing by the Norton Company under Navy contract and as reported in reference (b), showed that fatigue spalling was obtained at 800,000 psi Hertz stress on NC132 silicon nitride. In an effort to duplicate these results NAPTC obtained a test specimen identified in Table II as 73-23 for which a failure occurred under the Norton Company program at 800,000 psi. In addition, test rod 73-22 reported in reference (b) was also obtained from the Norton Company but no testing was conducted on this rod at NAPTC. The results of NAPTC and those obtained by the Norton Company (reference (b)) are compared in Table III. Data on test rod 73-22 is also included. The NAPTC tests were run well beyond the life obtained by Norton at the 800,000 psi stress level without failure. In addition, one test was run at a lower speed in an attempt to reduce the elastohydrodynamic film thickness and initiate failure through increased surface asperity interaction. However, no failure occurred after 54.4 million stress cycles. Close examination of the wear tracks produced by the Norton Company and those produced by NAPTC showed significant differences which may explain the differences in results. These wear track differences are discussed in detail later under the sub-section entitled "Examination of Wear Track".

Effect of Skidding -

25. Information on the effect of skidding (i.e. sliding with rolling) on the durability of silicon nitride was obtained accidentally during the course of this test program. In one test where the torque required by the test rod to drive the loading disks was excessive, skidding occurred and the machine was shut down in less than one minute. The excessive torque was caused by a tight fit of one loading disk on its

support bearing. Examination of the test rod showed wide, deep cracking in the wear track as shown photographically in Figure 8. This result indicates that the effect of skidding on the endurance characteristic of silicon nitride should be further investigated since the skidding phenomena occurs often in full scale engine bearings.

High Temperature Testing -

26. A limited amount of testing was conducted to determine the feasibility of testing silicon nitride at elevated temperatures on the RC fatigue tester. Seven tests were run at elevated temperatures at three Hertz stress levels as shown in Table IV. No failures occurred. Most of the tests were terminated due to loading disk fatigue failure. One test at 800,000 psi and 500°F ran to 17.9 x 10^6 stress cycles without failure. This is about three times the average life of M-50 steel at 800,000 psi run at ambient temperature. These tests showed that testing of silicon nitride at elevated temperature was feasible on the RC tester.

Effect of Silicon Nitride on Durability of M-50 Steel -

27. Since the potential use of silicon nitride in bearings is as rolling element (balls or rollers) material, it is of interest to know the effect of silicon nitride on the durability of steel. Although a test program was not run to determine this specifically, some information can be gleaned by examining the failure rate of the M-50 steel loading disks which were mated to the silicon nitride test rods. Table V compares the failure life of the loading disks run in contact with silicon nitride with those run in contact with M-50 steel. Data for the M-50 steel is available only at a 600°F test rod temperature condition. Since temperature is known to reduce fatigue life significantly (reference (f)), the life at ambient conditions will be several times that at 600°F. The limited data of Table V show that the fatigue life of the loading disks are poorer when run against silicon nitride. In addition the fatigue life decreases significantly with increased temperature. These data suggest that a program to thoroughly investigate the effect of silicon nitride on the fatigue endurance of M-50 steel be conducted under controlled test conditions.

Examination of Wear Tracks -

28. Test rods 73-23, 73-22 and 3 were examined with both an optical and a scanning electron microscope. In addition, surface traces across the wear track were made of test rods 73-23 and 3. The wear tracks are identified, with pertinent information, in Figure 9, for reference in the following discussion. Wear tracks with numbers preceded by a P were those run at NAPTC while those preceded by N were run under the Norton Company program. Examination of the wear tracks revealed that:

a. All the spalls include one or both edges of the wear track as shown in Figures 4 and 10. Closer examination of these wear tracks reveals cracking at the edge of the wear track as shown in Figure 11. This cracking is on both edges of the track and extends around the entire circumference of the test rods. Edge cracking remote from the spall is shown in Figure 12. This suggests that the spalls originated at the edge of the wear track and were initiated by the cracking. Figure 11 suggests that the fatigue spalls propagate by a) the formation of cracks transverse to the wear track and b) the flaking out of material between successive transverse cracks.

b. Wear tracks which do not contain spalls exhibit no cracking at the wear track edges. It may be that cracking is necessary to initiate spalling.

c. A typical as-ground surface is compared to the run surface within wear track P1 in Figure 13. Many of the grinding scratches apparent in the as-ground surface appear to be worn away in the run surface. The difference between as-ground and run surface is also apparent in Figures 11 and 12.

d. All the Norton run wear tracks, exhibited several grooves within the wear track as shown in Figure 14. None of the NAPTC wear tracks exhibited grooves. One of the grooves in Figure 14 is shown at successively higher magnifications. The surface within the groove appears to contain a higher density of surface pits than the area outside the groove. Surface traces of the wear tracks of test rod 73-23 were made. The traces for tracks N1, N2 and N3 are shown in Figure 15. The deepest grooving occurs in track N1 which was run at the highest Hertz stress (800,000 psi) and was the only run which experienced a fatigue spall. The largest groove (track N1) is about 0.008 inches wide and 0.00016 inches deep. For comparison, traces on NAPTC produced tracks (P2 to P5) are shown in Figure 16. All testing on these tracks was conducted at 800,000 psi Hertz stress. No grooves are apparent in the NAPTC tracks. In addition, no fatigue spalls were obtained in NAPTC tracks at this Hertz stress even though tests were run up to almost 10 times the number of stress cycles to which the failed Norton Company tests were run as shown in Table III. It is possible that the grooving in the Norton run tests played some role in the failure mechanism to accelerate fatigue. Such surface imperfections are known to initiate fatigue spalling in steel bearings. It is speculated that the grooves may have been caused by a combination of slight slipping (or skidding) between the test rod and the loading disks and poor surface finishing of the crown of the loading disks.

e. Microscopic examination of the HS110 silicon nitride test rod (designated as number 11) showed the as-ground surface to be peppered with black spots. It is believed that the spots have some depth (i.e. they are pits) because the density and the color intensity increased with the increased incident angle of the light, indicating that the black spots were caused by shadows. The other HS110 test rod (FM6) showed no such pitting. Unfortunately, no photographs of these specimens are available. The pits of rod number 11 can act as initiation sites for fatigue crack growth to occur, thereby accounting for its low fatigue life. Fatigue results on a test rod from the same billet of material, finished processed in exactly the same manner was reported in reference (b) by Norton Company (designated rod number 12). It too was reported to have poor fatigue life and surface pitting. The Norton Company believes that a combination of low density and poor finish processing caused the "pull-out" of material from the surface causing small pits.

TABLE I

SILICON NITRIDE TEST RODS

Test Rod Number	Material Designation	Density gm/cc	Remarks
FM6	HS110	3.15	Reported in Reference (a)
11	HS110	3.14	Reported in Reference (a)
73-22	NC-132	3.23 to 3.28	Reported in Reference (b)
73-23	NC-132	3.23 to 3.28	Reported in Reference (b)
1	NC-132	3.23 to 3.28	Purchased new from Norton
2	NC-132	3.23 to 3.28	Purchased new from Norton
3	NC-132	3.23 to 3.28	Purchased new from Norton

Note 1. All test rods except number 11 were finish processed as follows:

a. Rough grind with 100 grit diamond wheel

b. Grind with 320 grit diamond wheel to achieve final dimensions

c. Final finish by hand lapping with diamond impregnated leather strap.

2. The 320 grit grinding (step b of Note 1) was eliminated for rod no. 11 and a mechanical lapping procedure substituted to achieve final dimensions and finish.

TABLE II

CONTACT FATIGUE DATA

Test Rod Number	Material	Max Hertz Stress	Load, Lbs	Life, Million Stress Cycles to Failure	Lm-Mean Life-Millions of Stress Cycles
11	HS110	700,000	220	0.75 0.62 0.62 4.02 3.84	2.46
FM6	HS110	700,000	220	44.70^{s} 9.04^{s} 9.05^{s} 8.89^{s}	——
71	M-50 CVM Steel	700,000	330	8.13 6.98 5.98 9.89 4.99	7.18
11	HS110	800,000	320	0.32 0.72 2.60 7.17	3.45
FM6	HS110	800,000	320	9.14^{s} 9.00^{s} 35.2 ^{s}	——
1	NC132	800,000	320	186.9 ^{s}	——
2	NC132	800,000	320	3.43^{s} 344.6 ^{s}	
3	NC132	800,000	320	7.58^{s}	
73-23	NC132	800,000	320	191.0 ^{s} 187.0 ^{s} 273.0 ^{s} 148.9 ^{s}	——
71	M-50 CVM Steel	800,000	490	1.83 4.30 4.96 8.91 5.23	5.29
2	NC132	900,000	450	35.0	——
3	NC132	900,000	450	31.9	——

NOTE: All tests conducted at 12500 RPM.
S= Test suspended prior to failure.

TABLE III

COMPARISON OF NORTON COMPANY AND NAPTC FATIGUE RESULTS AT 800,000 PSI MAX HERTZ STRESS

Test Rod Number	Millions of Stress Cycles to Failure	
	NAPTC	NORTON
73-23	148.9^{s} 191.0^{s} 187.0^{s} 273.0^{s} 54.4^{s*}	28.3
73-22	—	29.1

S = Test suspended prior to failure.
* Test run at 5000 RPM.

NOTE: **Tests run at 12500 RPM unless otherwise noted.**

TABLE 1V

HIGH TEMPERATURE (500°F) TESTING OF SILICON NITRIDE

Hertz Stress PSI	Test Rod Number	Endurance Life Millions of Stress Cycles
400,000	1	55.5^{s}
400,000	2	187.5^{s}
600,000	2	51.2^{s}
600,000	2	9.3^{s}
800,000	1	17.9^{s}
800,000	1	1.28s
800,000	1	1.20s

S = Test suspended prior to test rod failure due to M-50 loading disk failure.

TABLE V

COMPARISON OF FAILURE RATE OF M-50 STEEL LOADING DISKS RUN AGAINST M-50 STEEL AND SILICON NITRIDE

Loading Disk Number	Lives - Hours to Failure		
	M-50 on Si_3N_4	M-50 on M-50	
	Ambient Temp	500°F	600°F
35	———	0.8	———
30	181.9	12.3	798 694
36	———	0.9	———
14	243	———	331

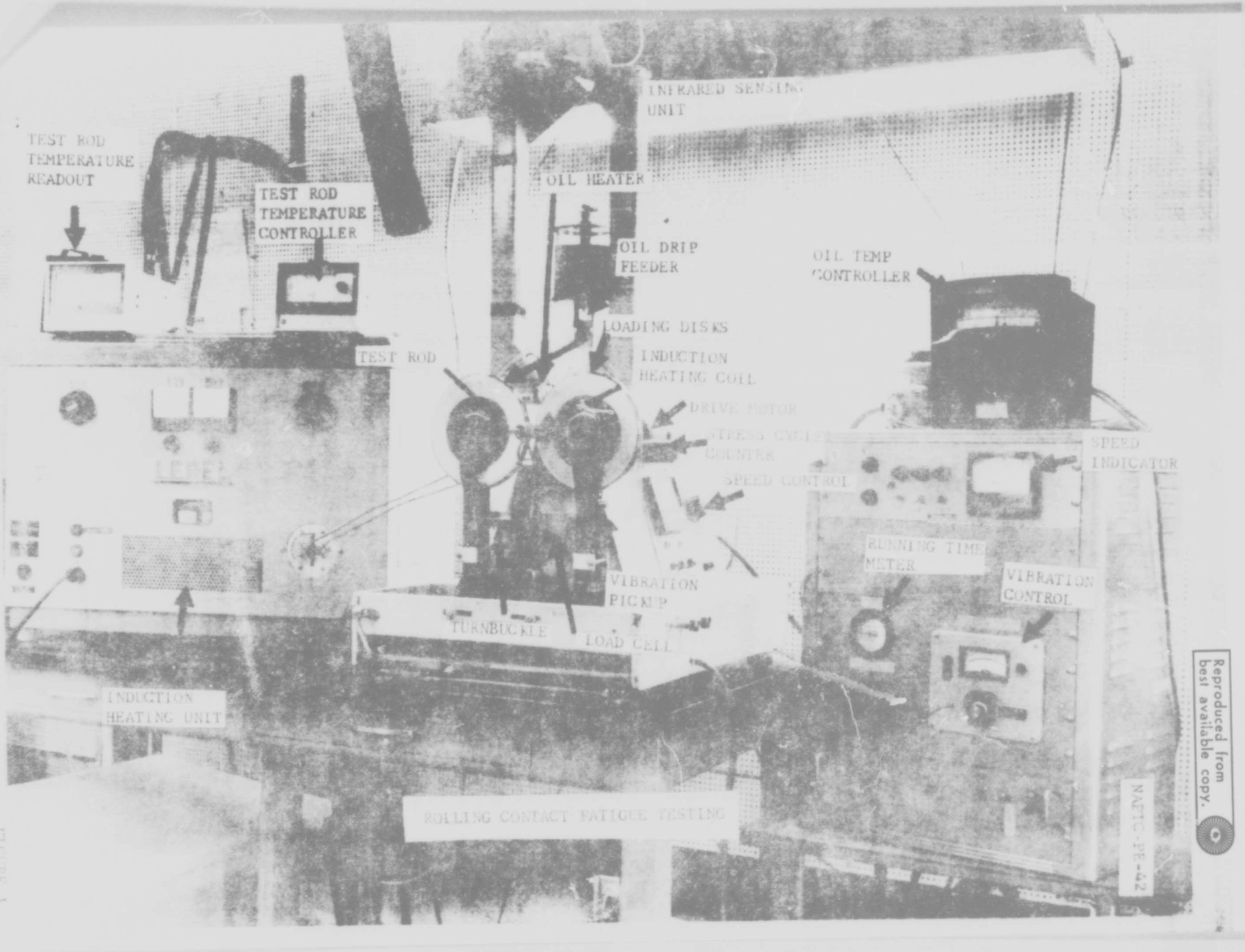
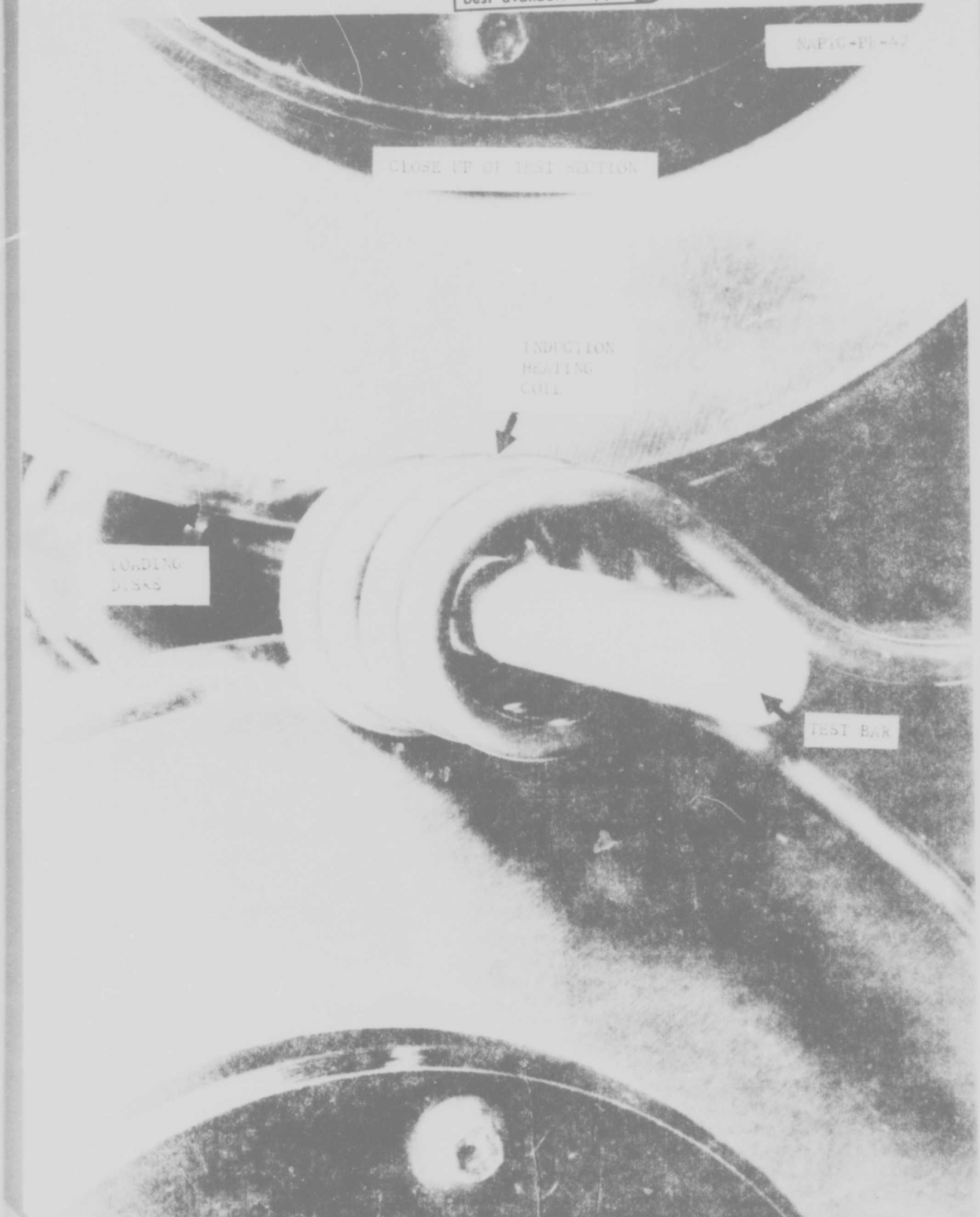

TEST ROD TEMPERATURE READOUT
TEST ROD TEMPERATURE CONTROLLER
TEST ROD
INFRARED SENSING UNIT
OIL HEATER
OIL DRIP FEEDER
LOADING DISKS
INDUCTION HEATING COIL
DRIVE MOTOR
STRESS CYCLE COUNTER
SPEED CONTROL
OIL TEMP CONTROLLER
SPEED INDICATOR
RUNNING TIME METER
VIBRATION CONTROL
VIBRATION PICKUP
TURNBUCKLE
LOAD CELL
INDUCTION HEATING UNIT
ROLLING CONTACT FATIGUE TESTING
NAPTC-PE-42

FIGURE 1



CLOSE UP OF TEST SECTION

FIGURE 2

ROLLING CONTACT RIG TEST ROD HIGH TEMPERATURE SYSTEM

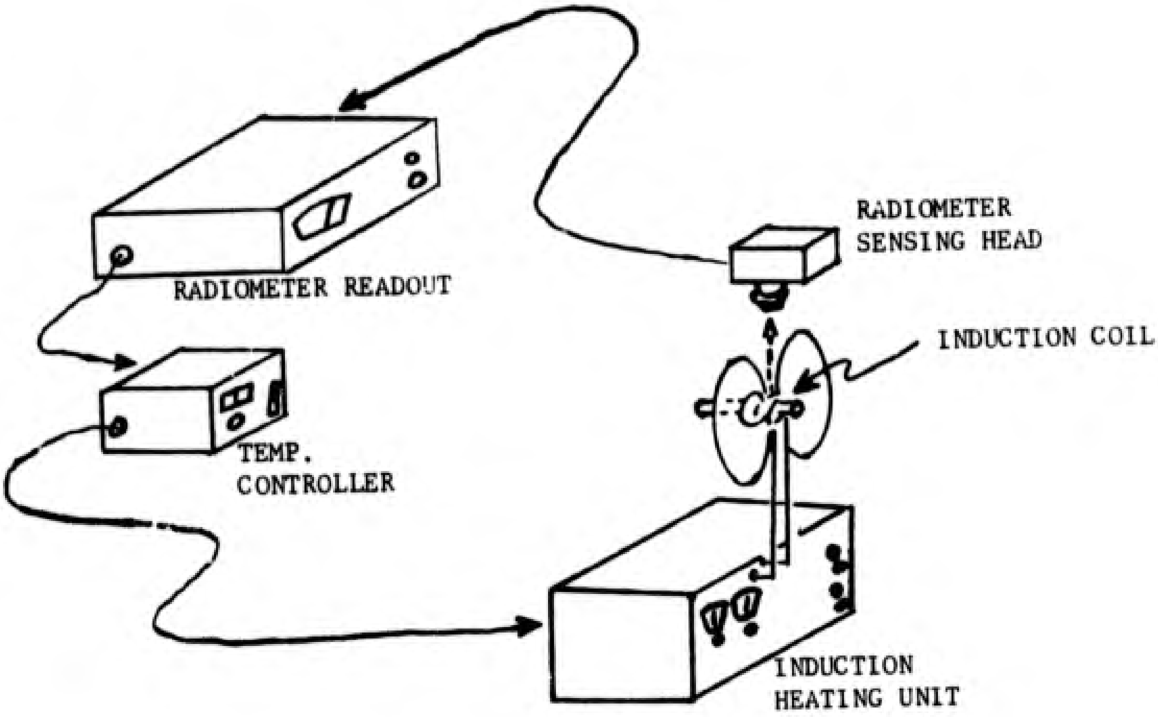
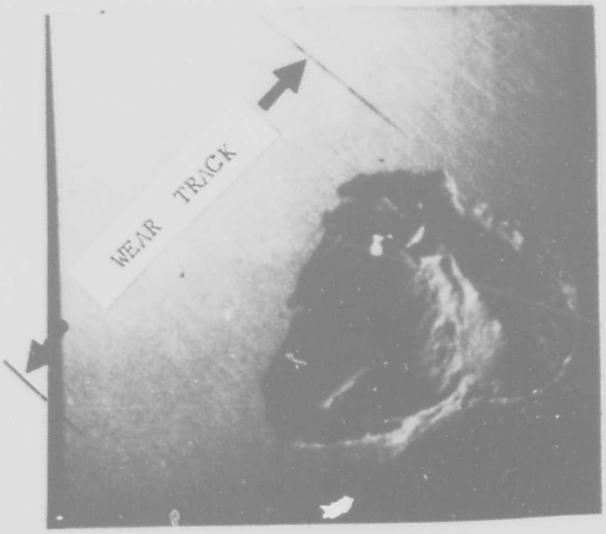


FIGURE 3

COMPARISON OF SPALLS FOR M-50 STEEL AND SILICON NITRIDE (50X)



SILICON NITRIDE

M-50 STEEL

FIGURE 4

MAXIMUM HERTZ STRESS vs APPLIED LOAD

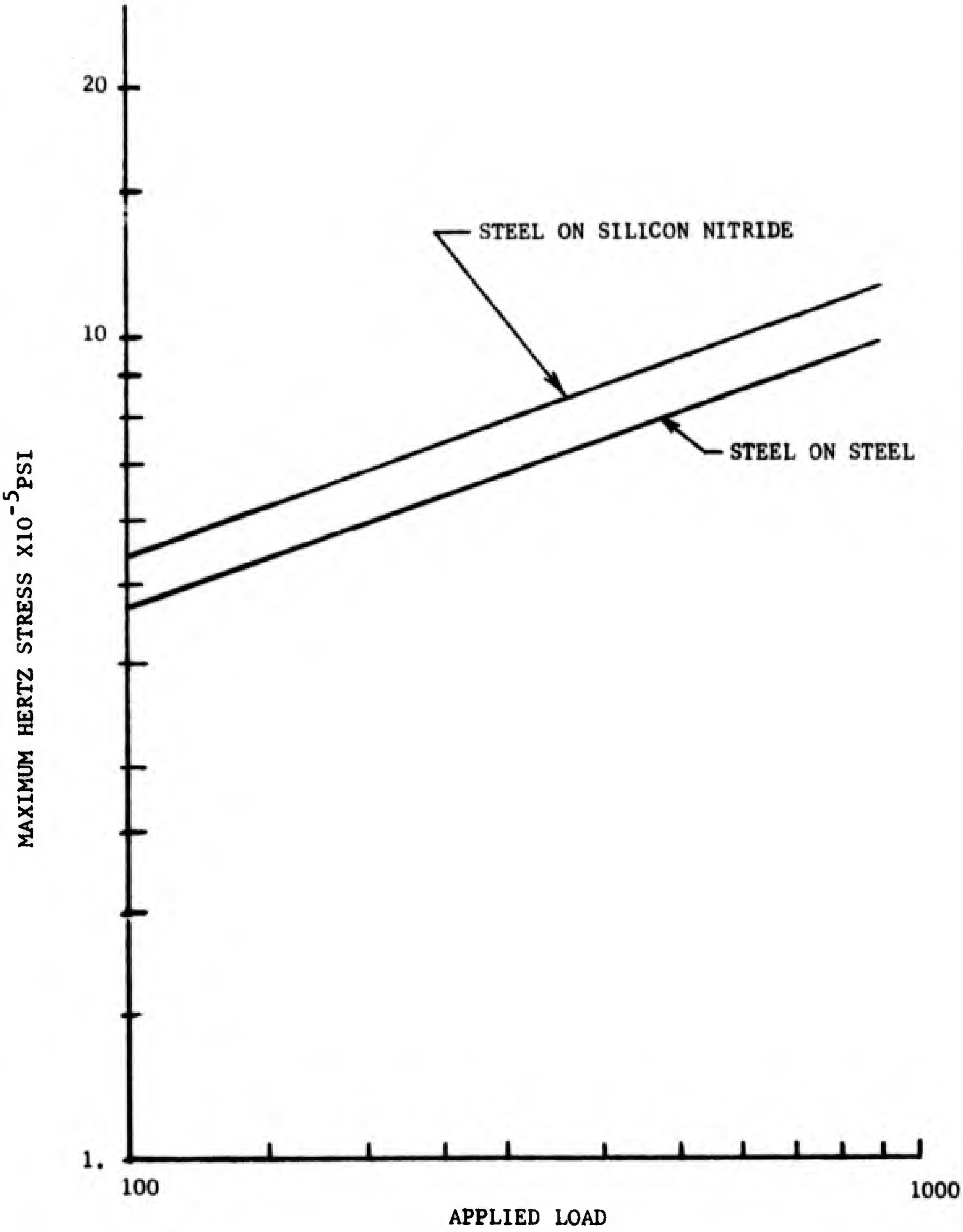


FIGURE 5

WEIBULL PROBABILITY CHART

Test Number		Article & Source	Sample Size	N	4
Date		Type of Test	Shape (Slope)	$\hat{\beta}$	2.8
P_μ	Mean	$\hat{\mu}$	Characteristic Life	$\hat{\eta}$	
$\hat{\beta}$			Minimum Life	$\hat{\gamma}$	

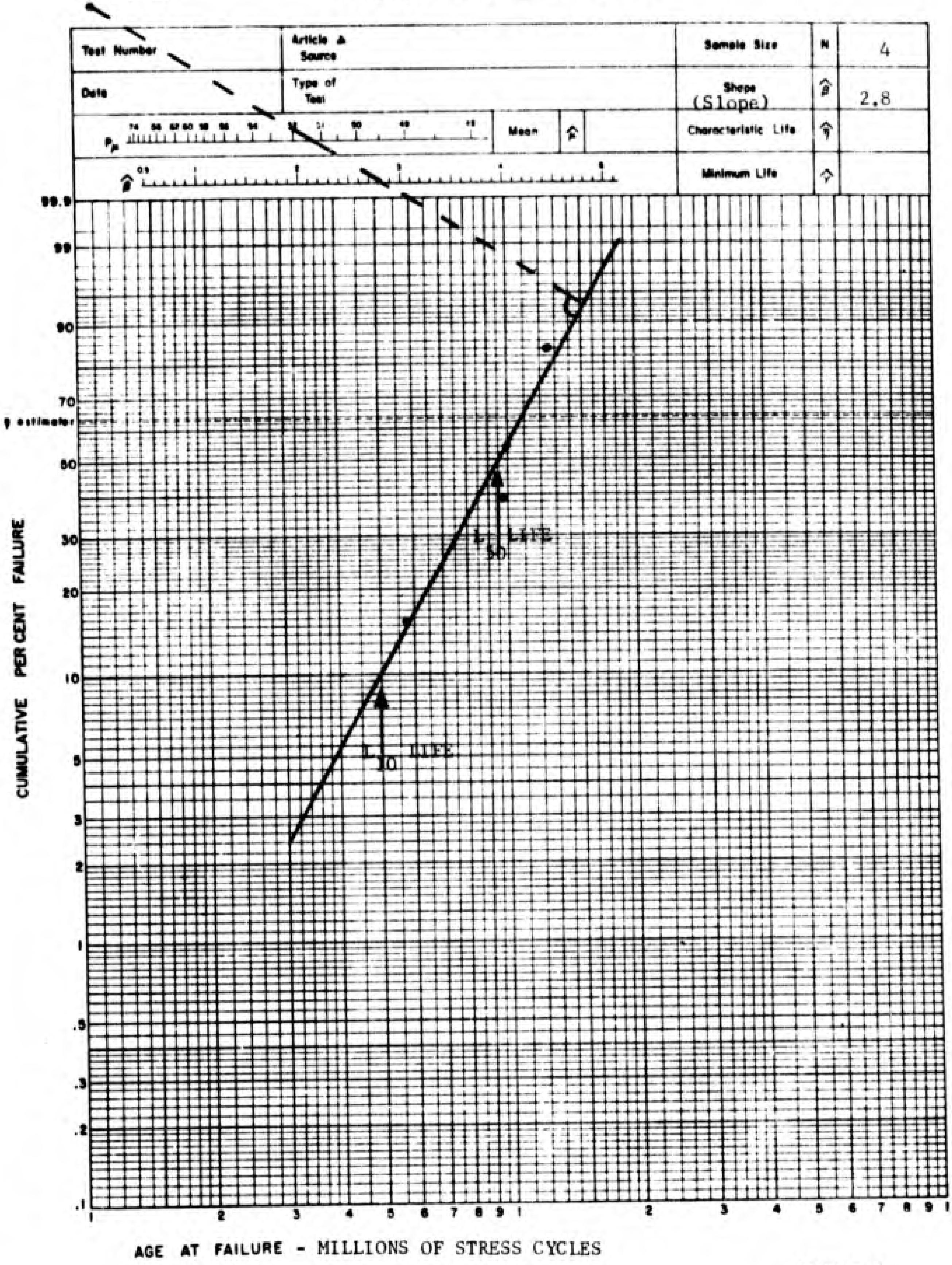


FIGURE 6

FAILURE COMPARISON OF M-50 STEEL vs NC132 SILICON NITRIDE

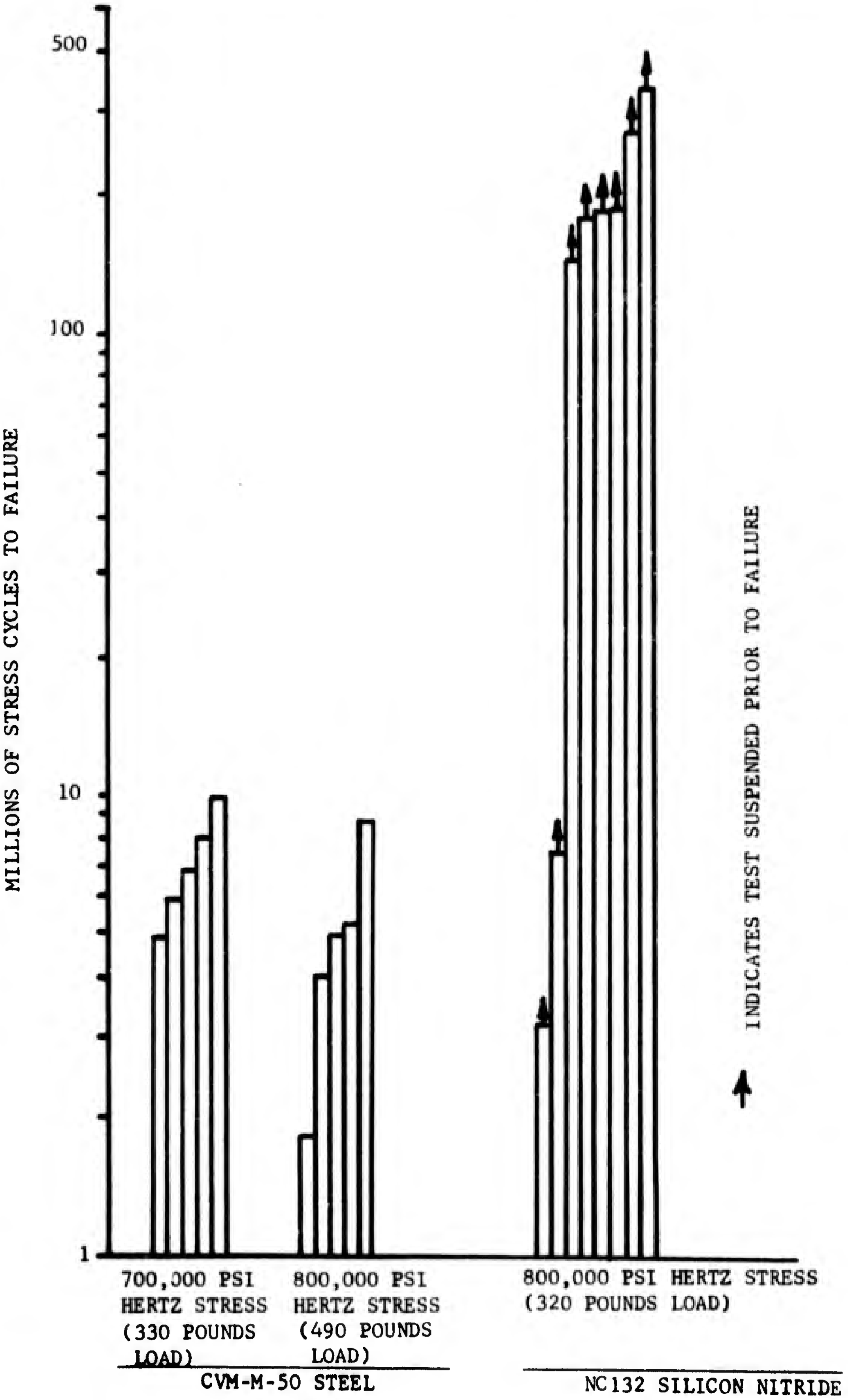


FIGURE 7

CRACKING OF SILICON NITRIDE TEST ROD DUE TO SKIDDING (16X)

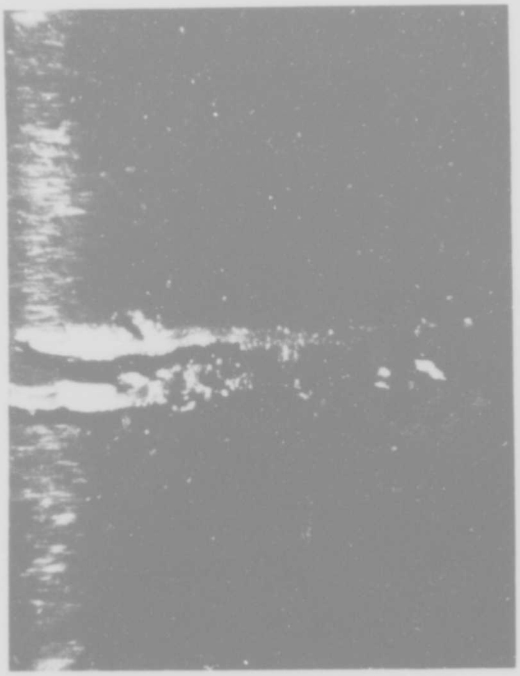
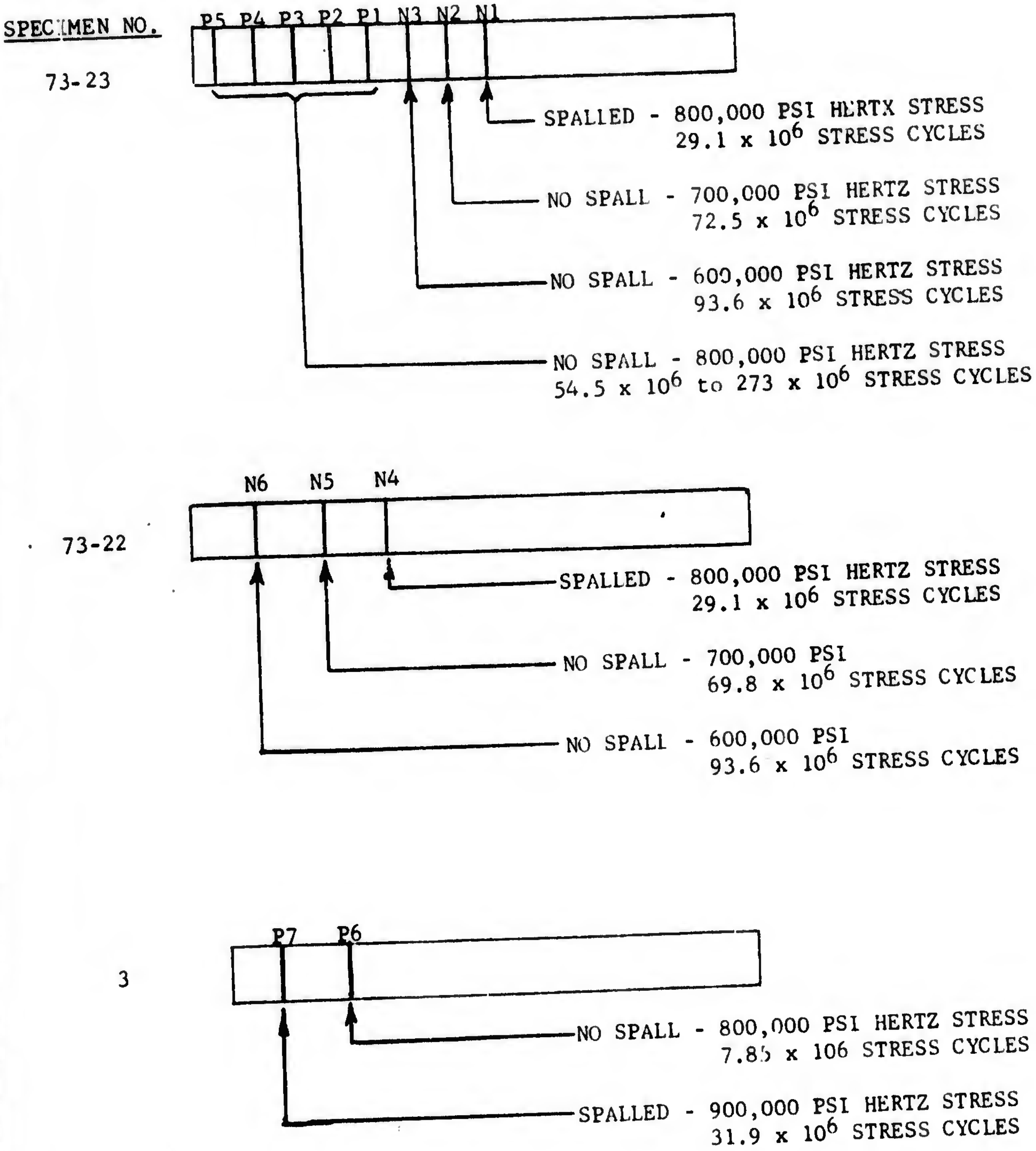


FIGURE 8

WEAR TRACK IDENTIFICATION OF SILICON NITRIDE TEST RODS



SPALLED - 800,000 PSI HERTX STRESS
29.1 x 10^6 STRESS CYCLES

NO SPALL - 700,000 PSI HERTZ STRESS
72.5 x 10^6 STRESS CYCLES

NO SPALL - 600,000 PSI HERTZ STRESS
93.6 x 10^6 STRESS CYCLES

NO SPALL - 800,000 PSI HERTZ STRESS
54.5 x 10^6 to 273 x 10^6 STRESS CYCLES

SPALLED - 800,000 PSI HERTZ STRESS
29.1 x 10^6 STRESS CYCLES

NO SPALL - 700,000 PSI
69.8 x 10^6 STRESS CYCLES

NO SPALL - 600,000 PSI
93.6 x 10^6 STRESS CYCLES

NO SPALL - 800,000 PSI HERTZ STRESS
7.85 x 106 STRESS CYCLES

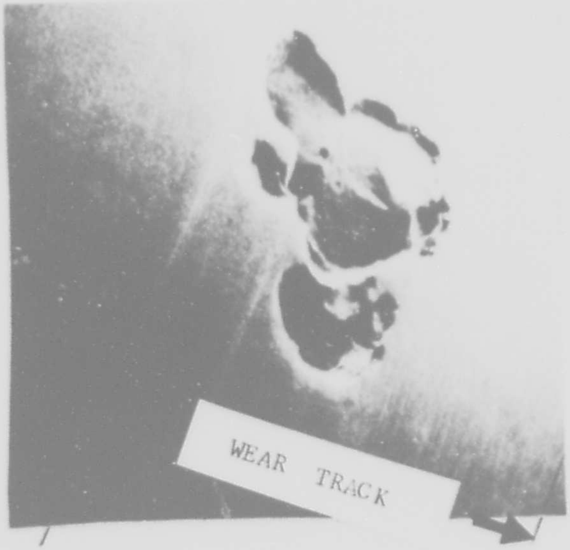
SPALLED - 900,000 PSI HERTZ STRESS
31.9 x 10^6 STRESS CYCLES

NOTE: 1. Wear tracks preceded by a P were run at NAPTC
2. Wear tracks preceded by an N were run by Norton Co.

FIGURE 9

FATIGUE SPALLING OF SILICON NITRIDE

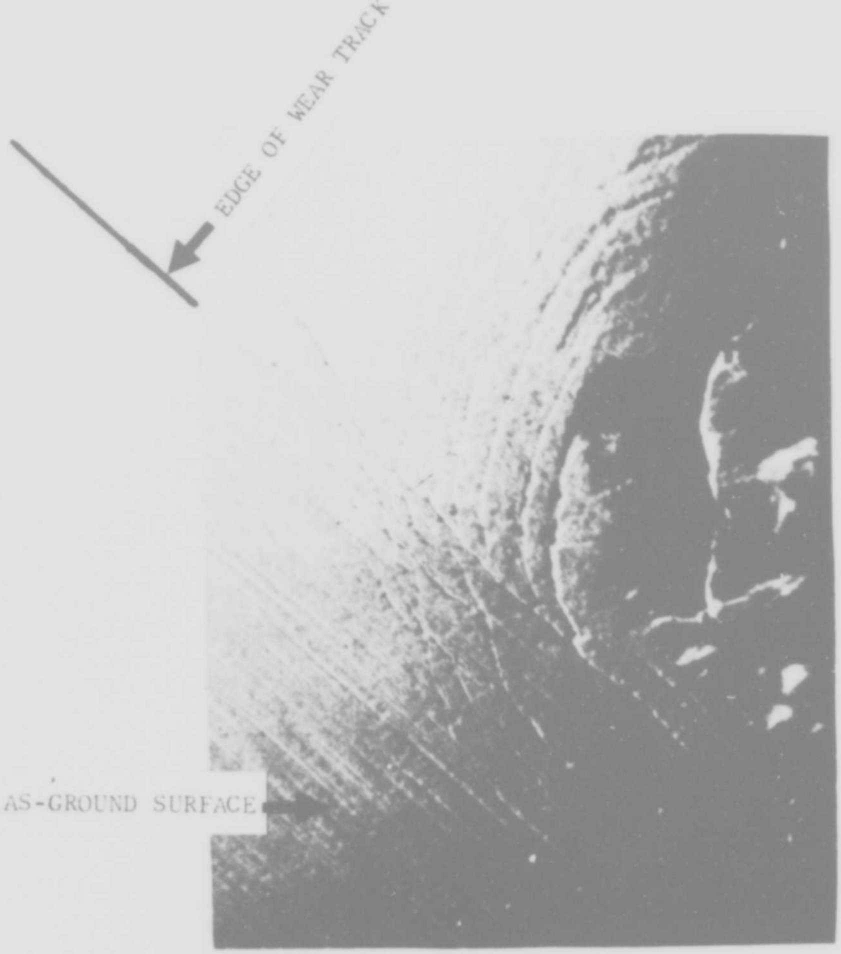
TRACK N4 (50X)



TRACK N1 (50X)

FIGURE 10

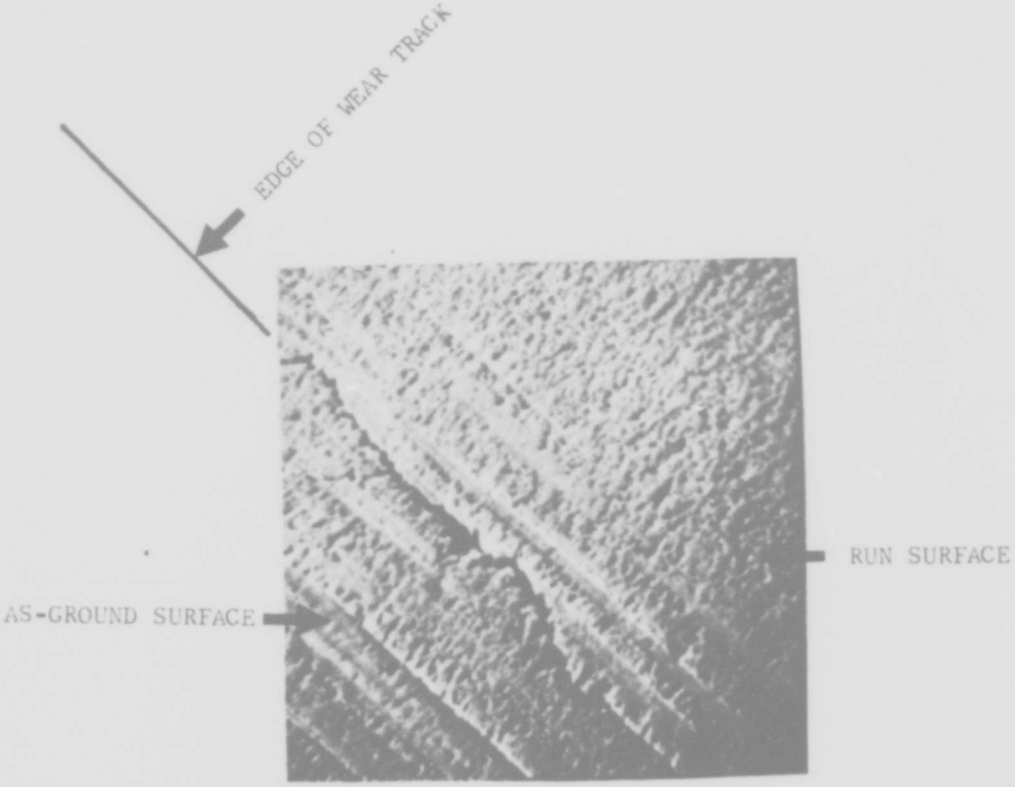
FATIGUE SPALLING AND EDGE CRACKING OF SILICON NITRIDE



TRACK N4 (150X)

FIGURE 11

SILICON NITRIDE CRACKING AT EDGE OF WEAR TRACK REMOTE FROM SPALL



TRACK N4 (500X)

FIGURE 12

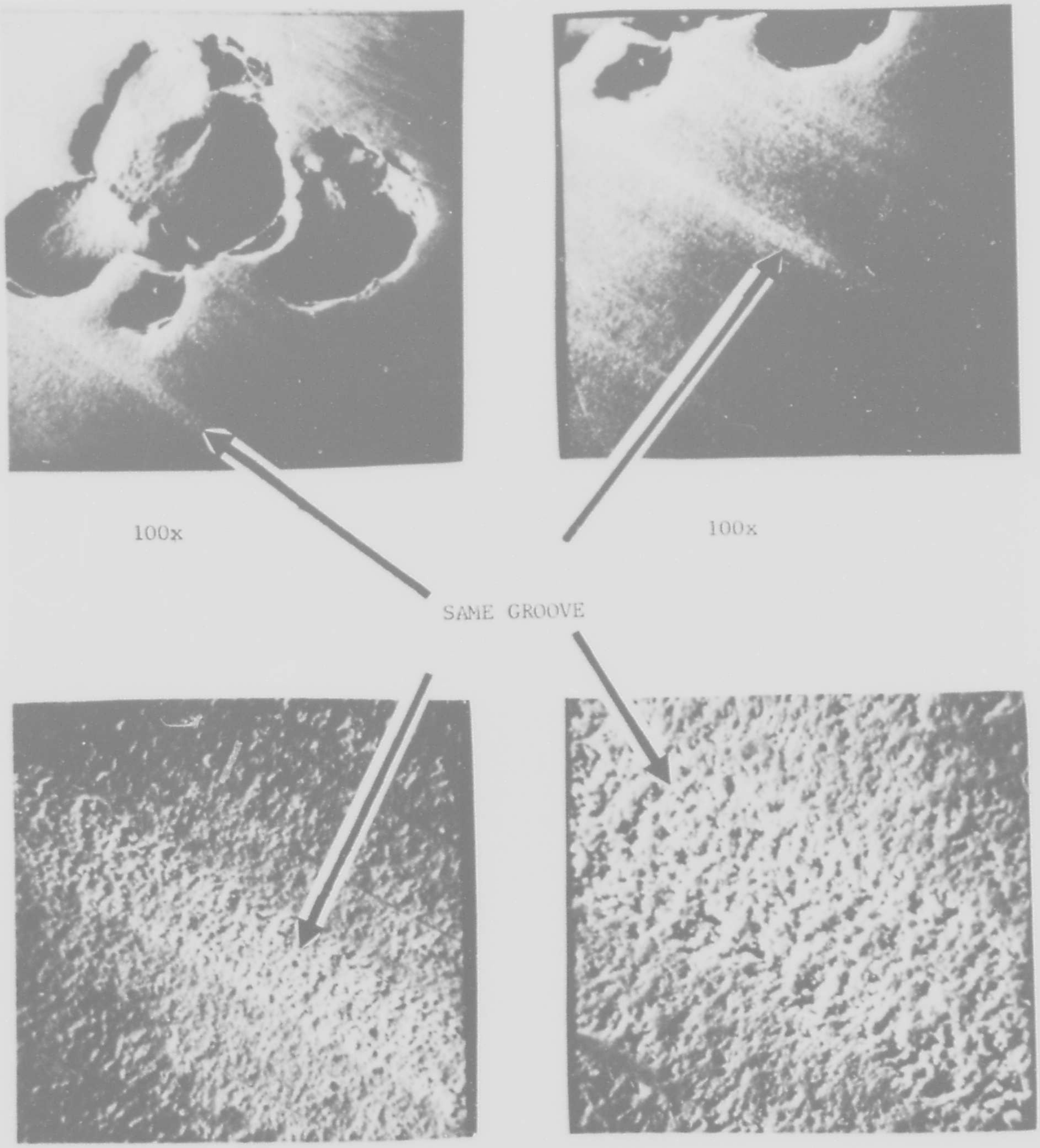
COMPARISON OF RUN AND AS-GROUND SILICON NITRIDE SURFACES

AS-GROUND SURFACE-TEST ROD
73-23 (1000X)

RUN SURFACE TEST ROD 73-23
TRACK P1 (1000X)

FIGURE 13

TYPICAL GROOVES IN SILICON NITRIDE WEAR TRACK
FROM TESTS PERFORMED BY THE NORTON COMPANY (TRACK N1)



100x

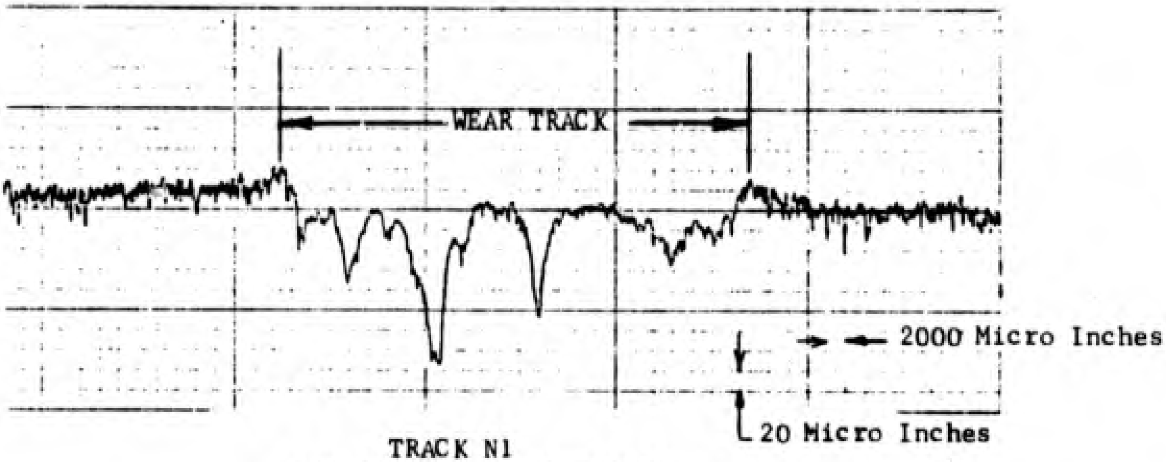
100x

500x

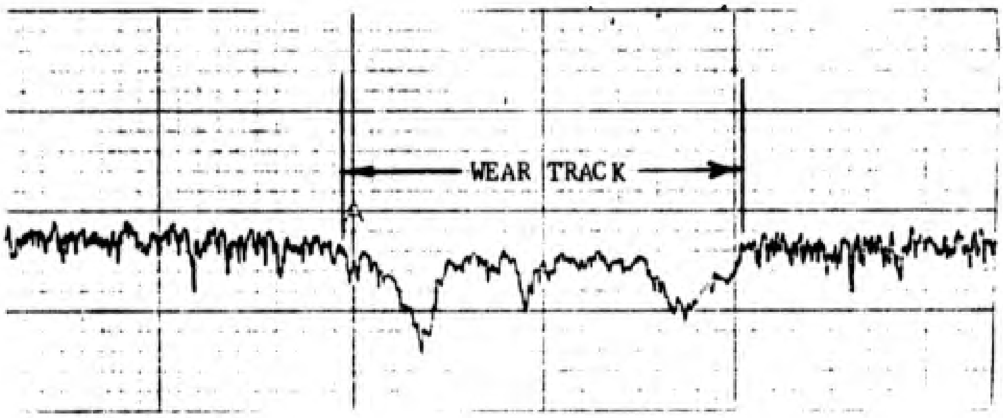
1000x

FIGURE 14

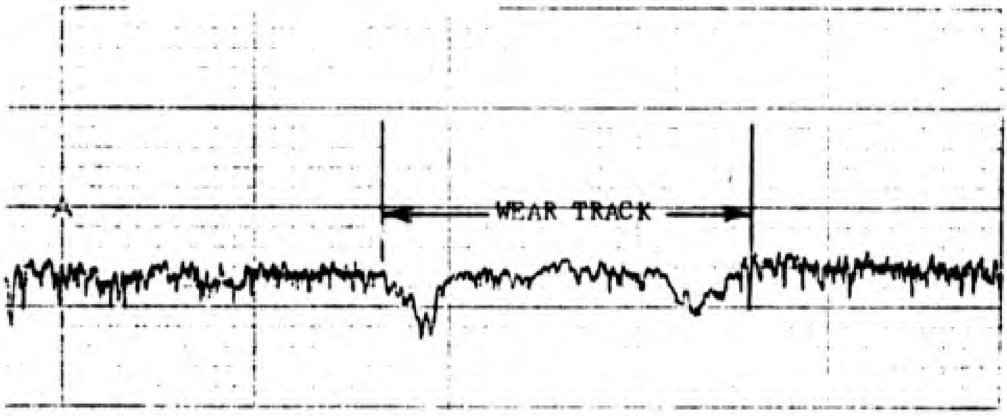
WEAR TRACK TRACES OF TEST ROD 73-23 RUN BY NORTON COMPANY



TRACK N1
800,000 PSI HERTZ STRESS



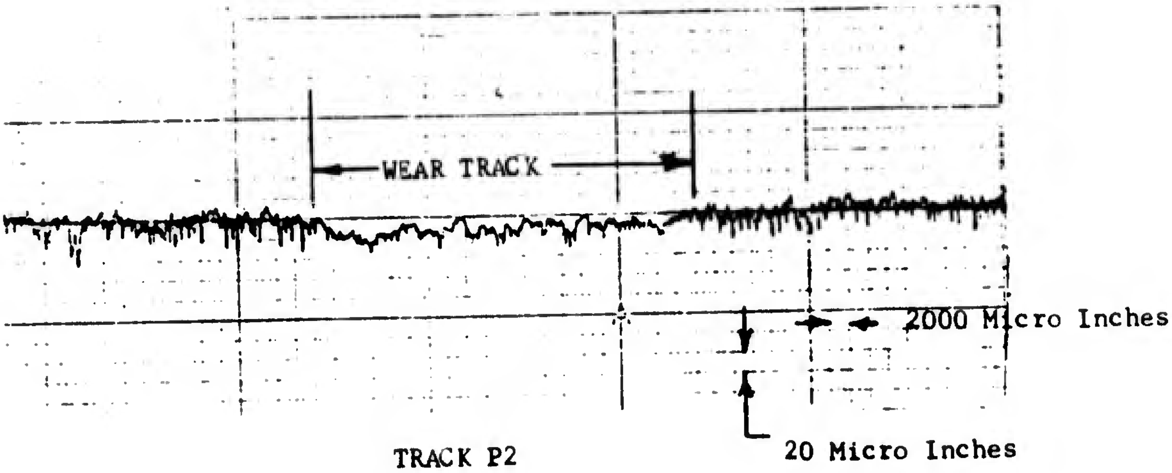
TRACK N2
700,000 PSI HERTZ STRESS



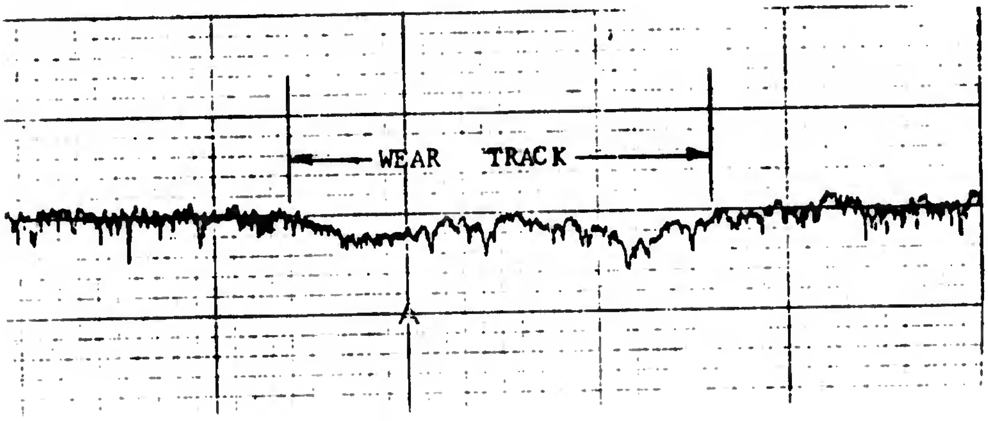
TRACK N3
600,000 PSI HERTZ STRESS

FIGURE 15

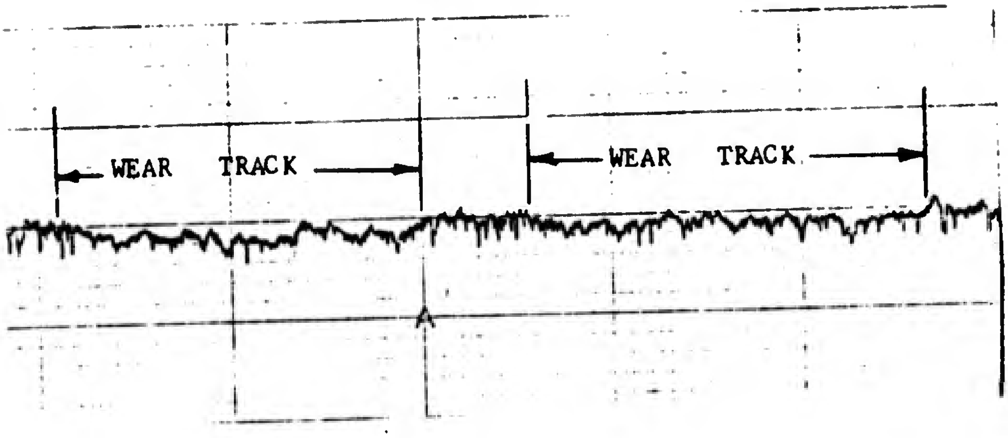
WEAR TRACK TRACES OF TEST ROD 73-23 RUN BY NAPTC AT 800,000 PSI HERTZ STRESS



TRACK P2



TRACK P3



TRACK P4

TRACK P5

FIGURE 16

29. REFERENCES.

a. Wheildon, W. M., Baumgartner, H. R., Sundberg, D. V. and Torti, M. L. "Ceramic Materials in Rolling Contact Bearings" Final Technical Report under NAVAIR Contract N00019-72-C-0299.

b. Wheildon, W. M., Baumgartner, H. R., Sundberg, D. V., Torti, M. L. "Silicon Nitride in Rolling Contact Bearings" Final Technical Report under NAVAIR Contract N00019-73-C-0193.

c. Valori, R. "Development of the Rolling Contact Fatigue Machine for the Evaluation of Fatigue Characteristics of Gas Turbine Lubricants as Related to Rolling Element Bearings" Naval Air Propulsion Test Center Report NAPTC-AED-1949 of June 1971.

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e. Johnson, L. G. "The Statistical Treatment of Fatigue Experiments" - Elsvier Publishing Co., Amsterdam, London, New York 1961.

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Appendix 1

Method of Temperature Calibration on Silicon Nitride Wear Track

1. The method of temperature calibration involves determination of the correct infra-red emittance level setting such that the temperature controller and readout equipment read the correct surface temperature. This is normally done on M-50 steel with the use of a calibration test rod on which thermocouple leads are tack welded such that the test rod itself forms part of the thermocouple junction on the wear track. Other types of thermocouples such as bayonet or even a welded junction which is then welded to the test bar produce large errors. The calibration test rod is placed in the machine, the temperature controller is then set at a desired temperature and the test bar is heated. The emittance setting is then varied until the control thermocouple temperature matches the tack welded thermocouple temperatures. Thus the emittance setting is determined.

2. Since silicon nitride cannot be used to form the junction of a thermocouple, a welded thermocouple junction was placed between the loading disk and the test rod and loaded to 325 lbs. The thermocouple was insulated from the loading disks by a piece of asbestos cloth. The controller was set at 500°F and the test rod heated. The emittance setting was varied so that a relationship was established between emittance setting and the thermocouple temperature reading. In order to approximate the temperature error, the M-50 steel calibration test rod was set up in the same manner (i.e. clamping the thermocouple between test bar and loading disk). The temperature controller was set at 500°F and the calibration rod heated. The emittance setting was varied and the clamped and calibration thermocouple temperatures were recorded until the temperature of the calibration thermocouple matched the control temperature. The difference in temperature between the clamped and calibration thermocouple (about 50°F) was assumed to represent the error in the temperature readings taken from the silicon nitride rod. The correct emittence setting for silicon nitride was then determined by shifting the setting to a new value. This new value compensates for the error in the previously established emittance setting vs thermocouple readout relatioship.