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FATIGUE ENDURANCE TESTING OF ION IMPLANTED ROLLER BEARINGS.(U)
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FATIGUE ENDURANCE TESTING OF ION IMPLANTED ROLLER BEARING

TRW BEARINGS DIVISION
RESEARCH AND DEVELOPMENT LABORATORIES
JAMESTOWN, NEW YORK 14701

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) Thirty 40-mm bore roller bearings from a single lot were divided into three groups of ten each. One group received chromium ion implantation, a second group received chromium plus phosphorus ion implantation, and the third group was untreated. The bearings were then subjected to fatigue endurance testing and the resulting data analyzed by use of the Weibull Distribution. No significant differences were found between endurance lives of the three groups. Failure mechanisms appeared identical in all bearings.		

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FOREWORD

This report describes the work performed by the TRW Bearings Division for the Naval Air Propulsion Center, Trenton, New Jersey under U.S. Navy Contract N00140-79-C-0323. The work described herein was conducted from December 1978 to October 1980.

The Government technical monitors were Daniel Popgoshev and Raymond Valori of the Naval Air Propulsion Center.

The program was conducted at TRW Bearings Division under the direction of Anthony T. Galbato and Harold E. Munson.

Appreciation is extended to James Hirvonen and Graham Hubler of the Naval Research Laboratory, Washington, D.C. for their efforts in designing the ion implantation fixtures and in conducting the ion implantation on the test bearings.

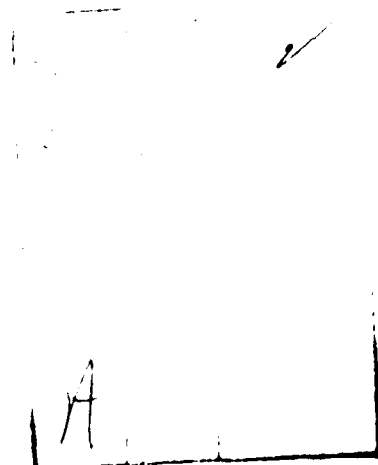


TABLE OF CONTENTS

	<u>PAGE</u>
. INTRODUCTION	1
. PROGRAM OUTLINE	2
. BEARINGS	4
. THE IMPLANTATION PROCESS	4
. ION IMPLANTATION	6
. TEST EQUIPMENT	7
. TEST PROCEDURE	8
. BEARING MEASUREMENT	9
. TEST RESULTS	12
. CONTACT STRESSES	16
. SURFACE FINISH	17
. RESIDUAL STRESS	18
. FAILURES	20
. SURFACE CHEMISTRY	22
. METALLURGICAL INSPECTION	23
. CONCLUSIONS	24
. REFERENCES	25
. TABLES 1 THROUGH 4	26
. ILLUSTRATIONS (FIGURES 1 THROUGH 25)	31

APPENDIX A1

APPENDIX A2

LIST OF TABLES AND ILLUSTRATIONS

	<u>PAGE</u>
TABLE 1 - MEASUREMENT DATA - BEARINGS	26
TABLE 2 - MEASUREMENT DATA - ROLLERS	28
TABLE 3 - RESIDUAL STRESS MEASUREMENTS	29
TABLE 4 - FATIGUE ENDURANCE LIVES	30
FIGURE 1 - MRC R108KD7 ROLLER BEARING	31
FIGURE 2 - ION IMPLANTATION PARAMETERS	32
FIGURE 3 - SCHEMATIC DIAGRAM OF RESEARCH TYPE ION IMPLANTATION SYSTEM	33
FIGURE 4 - SCHEMATIC DRAWING OF TEST MACHINE	34
FIGURE 5 - BATTERY OF FATIGUE ENDURANCE TEST MACHINES	35
FIGURE 6 - FATIGUE ENDURANCE TEST MACHINE	35
FIGURE 7 - ION IMPLANTED ROLLERS WITH DISCOLORED AREAS	36
FIGURE 8 - CIRCUMFERENTIAL PROFILE TRACE OF TYPICAL ROLLER	37
FIGURE 9 - FATIGUE ENDURANCE LIVES (WEIBULL CHART)	38
FIGURE 10 - SEM PHOTOS OF INNER RACE, S/N R8	39
FIGURE 11 - SEM PHOTOS OF INNER RACE, S/N R18	40
FIGURE 12 - SEM PHOTOS OF OUTER RACE REPLICATION, S/N R8	41
FIGURE 13 - SEM PHOTOS OF OUTER RACE REPLICATION, S/N R18	42
FIGURE 14 - SEM PHOTOS OF SURFACE OF ROLLER	43
FIGURE 15 - RESIDUAL STRESS MEASUREMENTS, RACES	44
FIGURE 16 - RESIDUAL STRESS MEASUREMENTS, ROLLERS	45
FIGURE 17 - PHOTOS OF TYPICAL ROLLER SPALLS	46
FIGURE 18 - PHOTO OF ROLLER WHICH BECAME EXTENSIVELY SPALLED	47
FIGURE 19 - SEM PHOTOS OF NEAR-CORNER AREAS OF ROLLER FROM S/N R7	48
FIGURE 20 - SEM PHOTOS OF NEAR-CORNER AREA OF TYPICAL UNFAILED ROLLER	49
FIGURE 21 - SEM PHOTOS OF INNER RACEWAY CORNER AREA, S/N R7	50
FIGURE 22 - SEM PHOTOS OF INNER RACEWAY CORNER AREA, S/N R8	51
FIGURE 23 - SURFACE CHEMISTRY OF SAMPLE ROLLERS	52
FIGURE 24 - SURFACE CHEMISTRY OF SAMPLE ROLLERS	53
FIGURE 25 - COMPARISON OF MICROSTRUCTURE, IMPLANTED AND UNIMPLANTED PARTS	54

INTRODUCTION

Ion implantation as a means of alloying the load bearing surfaces of gears and rolling element bearings used in Navy and aircraft propulsion systems, has the potential for solving costly problems relating to corrosion and premature surface failures.

Ion implantation is a process by which virtually any element can be injected into the near-surface region of any solid by means of a beam of high-velocity ions (usually tens to hundreds of keV in energy) striking a target mounted in a vacuum chamber. The bombarding ions lose energy in collisions with substrate atoms and come to a stop at depths of tens to thousands of angstroms in the host material. The major advantages of ion implantation over coatings and other methods of surface treatments are:

- a. No change in dimensions or surface character which allows the implantation of existing bearings without further processing,
- b. None of the interface bonding problems associated with coatings,
- c. Material bulk properties remain the same,
- d. Choice of alloying element is not limited by solid solubility or diffusion parameters.

Accordingly, ion implantation offers an attractive method of achieving corrosion resistance and improved tribological characteristics.

Consequently the Naval Air Propulsion Center (NAPC) has established and is managing a program to investigate the use of ion implantation for:

- a. Producing corrosion resistant alloys on M-50 steel bearing surfaces,
- b. Improving the tribological characteristics (wear, scoring, etc.) of bearing surfaces.

Rolling contact fatigue element tests conducted at NAPC have indicated that the ion implantation process is not deleterious to the fatigue life of the host material. The purpose of the program described herein was to carry the testing one step further and determine whether the fatigue life of full scale rolling element bearings is affected by the implantation of ion species which show the greatest improvements in the corrosion resistance of the substrate material.

PROGRAM OUTLINE

TRW Bearings Division fabricated thirty-four 40-mm bore roller bearings as a single lot from double vacuum melted (VIM-VAR) AISI M-50 tool steel. The original intent was to subject fifteen of the bearings to ion implantation while keeping fifteen others as a reference group. The other four bearings were for metallurgical or other destructive analysis. Before implantation was accomplished the program was modified to incorporate two different implantation species; groups of ten bearings each received the two different ion implantations, leaving ten bearings as a reference lot.

Races, raceway sidewalls and rollers were implanted by the Naval Research Laboratory in Washington, D.C. Components for ten bearings were implanted with chromium ions while those for the second group of ten bearings received phosphorus in addition to the chromium. An additional set of races was implanted with chromium ions and several extra rollers received each treatment. Components were returned to TRW Bearings Division where they were examined for comparison with pre-implantation characteristics, then assembled into bearings. The twenty ion implanted bearings and ten standard bearings were then subjected to fatigue endurance testing to determine if ion implantation affected bearing life. Following the test, bearings were examined for cause of failure and for any characteristics which might indicate a difference in performance between the three groups.

BEARINGS

All bearings in this program were MRC R108KD7 roller bearings.

They had the following characteristics:

TOLERANCES	- RBEC-5
BORE	- 40-mm, 1.5748 inch, nominal
O.D.	- 68-mm, 2.6772 inch, nominal
WIDTH	- 15-mm, 0.5906 inch, nominal
CONSTRUCTION	- Double flanged inner ring, Single flanged outer ring
RING MATERIAL	- AISI M-50, produced by VIM-VAR process
ROLLER MATERIAL	- AISI M-50, produced by VIM-VAR process
CAGE MATERIAL	- Silicon-Iron-Bronze, silver plated 0.0005-0.0020 inch thick per AMS 2412
ROLLER DESIGN	- 7-mm dia. x 7-mm long with modified crown
CAGE CONSTRUCTION	- 18 roller pockets, inner ring guided
INTERNAL CLEARANCE	- 0.0015-0.0020 inch

Figure 1 is a drawing of this bearing.

THE IMPLANTATION PROCESS

Ion implantation is not a coating technique. Implantation consists of forcibly injecting selected elemental ion species beneath the surface of materials by means of a high-energy ion beam from an accelerator (usually at tens to hundreds of kilovolts). This injection process produces an intimate alloy of the implanted and host elements without producing a sharp interface characteristic of most coatings and hence avoids the related adhesion problems.

The resultant depth distribution and alloy composition depend on the energy and atomic number of the projectile as well as on the atomic number of the host. Typically, depths of 0.01 to 1.0 micrometers are achievable with concentrations of up to 50 atomic percent. It should be stressed that ion implantation is not a thermodynamical equilibrium process and that metastable alloys can be formed without regard for the conventional considerations of solid solubility and diffusivity; since any elemental species can be implanted into any other material. Heating of the implanted alloy to sufficiently high temperatures will, of course, ensure equilibrium conditions, but several durable metastable (or amorphous) phases with potentially interesting physical properties have been formed by implantation. Figure 2 summarizes many of these factors pertaining to ion implantation for materials modification. The ability to control and reproduce the ion beam parameters listed in Figure 2 is especially important to its large scale commercial usage for implanting (doping) semiconductor wafers with high reproducibility (typically less than 3% dose difference on different wafers or between different points on a single wafer).

Figure 3 shows a schematic diagram of a typical research-type ion implantation system. As depicted, atoms are ionized in an ion source, accelerated to the desired energy, analyzed according to mass by a magnet to select the desired species, and then electrostatically raster scanned over the target to ensure dose uniformity of the implantation. The implanted dose (in terms of impurity atoms per unit volume) is obtained from the ion beam charge, the implanted target area, and the implanted species depth distribution.

ION IMPLANTATION

Naval Research Laboratory personnel reported the following relative to the ion implantation process on the bearings in this program:

<u>BEARING SERIAL NUMBER</u>	<u>ION</u>	<u>FLUENCE (ions/cm²)</u>	<u>ENERGY (keV)</u>	<u>APPROX. WT. % AT SURFACE</u>
R1-R10	Chromium	2×10^{17}	150	15.4
	Phosphorus	1×10^{17}	40	20
R11-R18, R20, R38, R39	Chromium	2×10^{17}	150	19

Temperatures which developed on components during the implantation process:

	<u>NORMAL</u>	<u>MAXIMUM*</u>
INNER RACES	400°F	550°F**
OUTER RACES	500°F	640°F
ROLLERS	390°F	650°F

* Maximum values were reached by some components for short periods of time.

** The temperature of the inner ring of S/N R17 exceeded 1000°F during implantation.

The rings of S/N R17 were not used for endurance testing but were reserved for stress analysis by X-Ray Diffraction.

TEST EQUIPMENT

Bearings were tested in a battery of four identical test machines. A test machine is shown schematically in Figure 4. Each machine ran four bearings at a time under the following conditions:

SPEED	-	7000 RPM
LOAD	-	2860 pounds radial
LUBRICANT	-	PVO STD. 6530 (MIL-L-23699)
OIL FLOW	-	One quart per minute per bearing by jet
TEMPERATURE	-	200°F - 210°F oil in

Lubricating oil was recirculated and was pumped through a 10 micron (nominal) filter before entering bearings.

An automatic shut-off device based on a chip detector was installed in the oil-out flow of each machine.

Machines were loaded hydraulically by a dynamic pumping system with a precise pressure regulator on each machine.

Each bearing was installed in the test machine with the flanged side of the outer ring oriented as shown in Figure 4 to provide axial stability to a test set-up. Shaft spacers and the central outer ring spacers were dimensioned to provide an axial looseness of 0.010 to 0.015 inch.

Oil temperature was maintained by electric immersion heaters in the oil sump, controlled by an automatic thermocouple-governed controller.

Figures 5 and 6 are photographs of test machines.

TEST PROCEDURE

Each bearing was assembled so that serial numbers of inner ring, outer ring, and cage were on the same side.

Bearings in a particular machine were selected to have the same radial clearance, if possible. It was never necessary to vary radial clearances of bearings within a machine by more than 0.0002 inch. When a failure occurred, all bearings were removed from the rig and arbor; unfailed bearings were reinstalled in their original positions along with a replacement bearing. When a test machine was removed from service, the unfailed bearing was installed in a different machine in the same position.

After a four-bearing spindle had been assembled and installed in a machine, lubricating oil was turned on and the spindle was permitted to sit stationary until temperatures had stabilized. Then the load was applied and the drive motor was started.

Each machine was set-up initially with bearings from all three groups. Typically, a machine could have one chromium implanted bearing, two chromium plus phosphorus implanted bearings, and a reference bearing. Test bearings were further distributed among the different machines so that bearings from each group were spread across all four test positions. As a bearing failed and was replaced, it was general practice to install a bearing from a different group. It had been anticipated that one group might have significantly longer life than others so that near the end of the test only that group would be running; this situation did not develop.

BEARING MEASUREMENT

Following fabrication, each bearing was checked in TRW Bearings

Division's Quality Assurance Department for the following parameters:

1. Inner ring bore
2. Outer ring O.D.
3. Diametral clearance
4. Width of rings
5. Width of inner raceway
6. Hardness inner ring
7. Hardness outer ring
8. Surface finish inner race
9. Surface finish outer race
10. Surface finish inner ring lands

Table 1 lists these data, along with measurements after ion implantation, on the twenty bearings which were so subjected.

All rollers were measured for O.D. and length. Sample rollers were checked for:

1. Surface finish
2. Flat length of cylindrical section
3. Crown drop
4. Corner break-out
5. Crown runout
6. Corner runout
7. Hardness
8. Roundness

Table 2 lists these measurements.

One set of rings and one roller were examined by Scanning Electron Microscopy (SEM) for surface characterization. Outer race examination was performed on a replica of the surface.

After ion implantation, measurements of rings, as noted, were repeated with the exception of width. Sample rollers were measured for diameter, roundness, surface finish and hardness. One set of rings plus a roller from each ion implanted group was examined by SEM for surface characteristics. There was no change in dimensional or characteristic measurements.

Following test, the ion implanted components which had been subjected to SEM before test were re-examined by the same means for changes in surface texture. A number of additional rollers and inner rings were likewise examined by SEM in an attempt to pinpoint failure mechanisms.

The following sample rollers were examined by Energy Dispersive X-Ray (EDXR) analysis to evaluate the near-surface chemistry:

1. New - not ion implanted
2. New - chromium implanted
3. New - chromium plus phosphorus implanted
4. Tested - chromium implanted
5. Tested - chromium plus phosphorus implanted

Two additional bearings, S/N R17 (chromium implanted races) and S/N R37 (a reference bearing), plus sample implanted and unimplanted rollers, were tested for residual stress by X-Ray Diffraction Analysis. Values were measured at the surface and at various depths up to 0.007 inch,

with stock removal by chemical polishing to permit measurement at locations below the original surface. Table 3 lists the data. Note that bearing S/N R17 was the one whose rings exceeded 1000°F during implantation, as stated earlier.

Ion implanted components were examined visually upon return from Naval Research Laboratory. Some rings were somewhat discolored on the faces, with a light brown stain. The inner rings of S/N R3 and R4 were most noticeably discolored. Naval Research Laboratory personnel indicated that this marking came from contact with a heat sink used during implantation.

Many of the rollers showed bands, like shadows, running axially across the surface. Occasionally the discoloration was wedge shaped (see Figure 7). Measurements of roller diameter of sample rollers, with resolution of a few microinches showed no variation corresponding to the coloration. Figure 8 is a trace of the O.D. of a roller which had distinct markings. Surface finish measurements indicate a difference of approximately 0.5 microinch between dark and shiny areas with the dark areas having the higher reading. Naval Research Laboratory personnel identified the roller discoloration as aluminum oxide of an unknown source. Aluminum oxide may be the result of the finish grinding and lapping operations (ref. 1).

Following test, the bands could still be seen on some rollers. Where bands could be identified on failed rollers there appeared to be no correlation with failure location.

A tested roller exposed to EDXR chemical analysis showed aluminum still present at the surface.

TEST RESULTS

A total of thirty-two (32) MRC R108KD7 roller bearings were subjected to fatigue endurance testing under previously described conditions. These bearings were made up of the following groups:

10 bearings,

S/N R1 through R10

- Chromium plus phosphorus
implanted

10 bearings

S/N R11 through R16,

R18, R20, R38, R39

- Chromium implanted

10 bearings

S/N R22, R23, R24, R26

R28, R29, R30, R31,

R32, R36

- Reference Bearings

2 bearings

S/N R33 and R34

- Same as Reference bearings
except that rollers were
from a different lot

Endurance life data are summarized in Table 4. These data are plotted on a Weibull Chart, Figure 9. The endurance life of S/N R38, the only failure involving any component except rollers, is omitted from the chart. The chromium plus phosphorus implanted bearings ran 90% and the chromium implanted bearings ran 110% as long as the reference bearings at the L-10 level. These differences are not statistically significant. The calculated 90% confidence bands (ref. 2) based on the test data from the Reference Lot are superimposed on the Weibull Chart and effectively encompass all datum points.

There are two unexpected aspects of this testing:

1. Overall lives were shorter than expected
2. All failures involved rollers

The calculated life for this bearing by the AFBMA method neglecting material and lubrication factors, but considering the geometry of the crowned portion of the rollers, is 15 hours. Life adjustments are:

D	(material factor) for M-50	= 2
E	(melting practice factor) for Vacuum Arc Remelt	= 3
F	(lubrication factor)	= .25

There is considerable opinion that "E" should be higher than 3 for vacuum induction melt - vacuum arc remelt (VIM-VAR) processed bearing steel but currently no separate value has been established. Using the above factors the calculated L_{10} life for the bearing under these conditions is $2 \times 3 \times .25 \times 15 = 22.5$ hours. Since the L_{10} lives obtained in test were 2.3X to 3.2X this value, overall performance was not unreasonable.

In fatigue endurance testing of bearings, the majority of failures usually occur in the inner races. Thus, a distribution of failures which is almost entirely limited to rollers is unusual. There was no apparent difference in failure mechanism between ion implanted rollers and untreated rollers, so the fact that rollers rather than races failed is largely incidental to this program.

However, bearing components have been examined in an attempt to ascertain the cause of failure. Certain facts which relate to the question are:

1. The rollers were slightly softer (0-2 points on the Rockwell C scale) than were the rings;
2. Fatigue spalls appeared to have generally started on the crowned portion of the rollers near the corner;
3. The crowned portion of the rollers adjacent to the corners were frequently burnished and sometimes had microscopic superficial spalls;
4. A few "unfailed" rollers had microscopic spalls in the crowned area at some distance from the corner; some of these were surface initiated but some could not be so defined;
5. When a spalled roller ran for some significant length of time after failure, the spalled area extended length-wise across the roller;
6. If an extensive spall was not rectangular in surface shape it tended to be widest near a corner of a roller;
7. Raceways were generally in good condition with occasional dents.

8. Calculations indicated relatively high stresses at the ends of the rollers, although these stresses were somewhat less than those in the central portion of the rollers.
9. Measurements of spalls showed greater depth in the central flat than near the end, indicating that stress calculations are valid. Typical values of the depth were 0.008 vs. 0.0045 inch.
10. Electron beam microscopy showed superficial spalls starting a few thousandths of an inch from the corner break, resulting from a combination of scuffing (due to skewing) and heavy load.

Rollers tend to wobble or skew as they travel around a race, particularly in an unloaded or lightly loaded condition. In this test each roller was unloaded half of the time, then very heavily loaded as it passed through the stressed zone. Some skewing occurred in these bearings and is evident from a slight "dog bone" wear pattern in the cage pockets. Roller end wear was negligible, however. The surface distress which developed near the ends of many rollers presumably occurred as rollers were forced to make adjustments in direction under heavy load; because of the heavy load the surface distress often manifested itself as microspalling.

It seems likely that a microspall occasionally developed into a full fledged spall. Because of the very heavy load, loss of a small amount of supporting surface caused extremely high stresses

to adjacent areas so the spalled area extended rapidly. The fact that races generally did not spall while rollers were failing is probably due to the fact that rollers were softer than rings.

CONTACT STRESSES

Appendix A presents computer print-outs of stresses, deflections, endurance life, etc. relative to the MRC R108KD7 roller bearing operating under the specified conditions. The data in A-1 were based on a roller flat length of 0.0920 inch while the data in A-2 used a flat length of 0.1720 inch. These values were the minimum and maximum values, respectively, for the flat length of the modified crown of the rollers used in this test. The computer program used to calculate bearing performance was Franklin Institute's GENROL, Level 24 (ref. 3). In setting up the input data a mounted radial clearance of 0.0015 inch was used, based on a maximum unmounted clearance of 0.0020 inch modified by a loss of 0.0005 inch due to press fit of the inner ring on the shaft. The computer program divided the effective length of each roller (total length less two corners) into 20 laminae of equal width and calculated the stress on each.

The calculated mean Hertz stress on the central portion of the most heavily loaded roller was approximately 300,000 psi. The calculated Hertz stress on the most outboard laminae was approximately 25,000 to 50,000 psi less than the central area as calculated by the GENROL program indicating that the condition of "edge loading" was being approached.

In a cylindrical roller bearing operating under heavy load, the stressed area of the raceways deflect. At the edges on either side of the loaded area, the change in profile of the raceway tends to produce stress concentrations which are significantly higher than Hertz stress formulas would indicate. The geometry of rollers is modified from true cylinders by "crowning" to provide relief near the ends and thus prevent edge loading. However, edge loading can still occur if the load is heavier and hence raceway deflection is greater than the crowned relief can accommodate. The high stresses produced by edge loading produce fatigue spalls near the ends of the rollers or at the edges of the raceways.

A roller with maximum flat length would be most susceptible to edge loading effects. Failed rollers were checked for length of central flat and location of this flat. All fell within specified tolerances and most were very close to the midpoint of the range.

SURFACE FINISH

Figures 10,11,12,13, and 14 are scanning electron microscope (SEM) photos of selected components at 4700 X magnification. All SEM photographs were taken at Calspan Laboratories, Buffalo, New York. Figures 10 and 11 show segments of the raceway surfaces of S/N R8 as manufactured, after ion implantation, and after running. An attempt was made to take these photos at the same spot based on an index mark on the ring face, but we were unable to locate the exact point on the race each time. Figure 12, and also Figure 13, are SEM photos of replicas of the outer race surface; replication was necessary because the configuration of the outer ring precluded

direct examination. Figures 11 and 13 show segments of the raceway surfaces of S/N R18 after ion implantation and after running. S/N 8 and S/N 18 are representative bearings demonstrating the two different ion implantation species involved in this program. Figure 14 shows segments of surfaces of a new roller; a chromium plus phosphorus implanted roller; and the latter roller after test in bearing S/N R8. The new roller is not the same one as is shown in the other sections of Figure 14.

The photographs give some indication of a blending of sharper features of finish by the ion implantation; however, surface finish measurements, as shown in Table 1, do not indicate any significant difference. Following test the SEM photographs show both a peening over of grinding marks and an apparent roughening, but the original finishing marks are still clearly visible.

Measurement of surface finish on sample tested but unfailed parts indicated an increase of inner race values from the 4-5 microinch range to 6-8 microinches. Outer raceway finish values increased from the 3-5 microinch range to 5-6 microinches. Sample roller surfaces measured 3-4 microinches. There was no discernable difference in surface finish performance between implanted bearings and reference bearings.

RESIDUAL STRESS

Table 3 and Figures 15 and 16 present data on residual stresses developed in implanted and reference bearing components. Normal grinding and finishing operations produce relatively high residual

compressive stress on the surface of a hardened part. At a short distance below the surface, these stresses decay to essentially a no stress condition but pass through a zone of low tensile stress. Thus, the residual stress patterns of the reference bearing components were quite normal.

The ion implanted parts followed the same general residual stress patterns as the reference parts. It had been suggested that ion implanted components might have higher surface stresses than reference parts because of the energy involved in impinging ions into the surface. Actually, the ion implanted races showed lower stresses at the surface than did the reference bearings, and the stress pattern of the inner race of S/N R17 deviated somewhat in details from the other rings. This particular ring overheated during the implantation process (temperature exceeded 1000°F) and the high temperature probably resulted in some stress relief. Unfortunately this inner race was the only implanted one which was not required for fatigue endurance testing.

Residual stresses were measured by X-Ray Diffraction in the TRW Bearings Division Materials Laboratory. To obtain stress values at points below the original surface, parts were chemically polished to remove stock to the required depth. The measurement by X-Ray Diffraction involves an averaging of values over a depth of approximately 0.00015 inch; therefore the depths listed on Table 3 and on Figures 15 and 16 are the distances from the original surface and the measured stresses include data developed from material slightly deeper than the nominal depths.

FAILURES

All failures except S/N R38 involved spalled rollers. S/N 38 experienced a spalled inner ring at less than half the life of any other failure. This anomalous failure is omitted from the Weibull analysis shown on Figure 9.

Figure 17 shows photographs of typical spalls, occurring in rollers in bearings S/N R6, R11, and R26. These rollers were chromium plus phosphorus ion implanted; chromium ion implanted; and unimplanted, respectively. The three failures appear to have been produced by the same mechanism and to have progressed in the same manner.

In an attempt to determine if the observed roller failure pattern was characteristic of a particular lot of rollers, a second lot of rollers was obtained. This additional lot was made from VIM-VAR M-50 tool steel. Its hardness was the same and rollers could be matched with existing races to meet radial clearance specifications. Crown geometry was somewhat different, as noted in Table 2; this would produce lower stresses on the outboard laminae.

Rollers from the second lot were installed in bearing S/N R33 and R34. Both bearings failed from the same mechanisms and at comparable times as bearings having the original lot of rollers.

Figure 18 shows a spalled roller, in bearing S/N R3, which ran for some period of time after failure initiated. Presumably, failure started on one side, then progressed across the whole

effective length of the roller and widened somewhat. This pattern of spall extension is found in representative rollers with both implantation species and in the reference group.

Examination of unfailed rollers shows some scuffing near the corner break. Figure 19 shows SEM views of the corners of a roller from S/N R7. This bearing ran 420 hours without failure. The roller scuffing shown in this roller appears considerably more severe than in most rollers. Back from the corners are areas of very fine pitting.

A more typical condition than the severe scuffing of Figure 19 is microspalling which occurred in many rollers a few thousandths of an inch back from the corner. Figure 20 shows SEM views of areas near the corners of a roller from S/N R16; this is typical of many rollers.

Figures 21 and 22 are SEM photos of inner raceway corners. Since the raceway corners have smaller radii than the roller corners, contact is not made between roller and race within 0.015 inch or more from the side wall. Figure 21, showing the corners of S/N R7, has scuffed areas corresponding to the contact with the scuffed rollers. Figure 22, showing the corners of S/N R8, a bearing which had a spalled roller, has much less pronounced scuffing. Typically, races show much less scuffing, microspalling, or denting damage than do rollers.

SURFACE CHEMISTRY

Figures 23 and 24 are photos of Energy Dispersive X-Ray (EDXR) chemical analyses of the surface of sample rollers involved in this program. Figure 23 provides a comparison of a new roller, an unused chromium ion implanted roller, and a tested roller having chromium ion implantation. Figure 24 is comparable to Figure 23, differing in that the rollers were subjected to chromium plus phosphorus ion implantation.

In all the photos of Figure 23 and 24, the FeK_β line is used as reference. This is practically the same height in all cases. The chromium line in the unused implanted rollers can be seen to be higher than the corresponding line in tested rollers, and both are higher than the chromium line in the new roller. M-50 tool steel contains 4% chromium as manufactured; the chromium content of the surface is shown to be enriched by implantation with partial loss of the increase during bearing operation.

M-50 tool steel contains phosphorus as a trace element only. Figure 24 shows a phosphorus line on the implanted rollers, both new and tested, with little difference between the two.

Aluminum is present in M-50 tool steel only as a trace element. In Figure 23, the aluminum line on the tested roller is believed to be related to the aluminum oxide which discolored portions of the surface of many rollers (Figure 7).

METALLURGICAL INSPECTION

Sample inners, outers, and rollers - implanted and unimplanted - were sectioned and subjected to metallurgical inspection near the surface. No difference in microstructure could be observed between implanted and unimplanted parts.

Figure 25 shows a comparison of the microstructure of the inner race of S/N R27, which was not implanted and the outer race of S/N R38, which was subjected to chromium ion implantation. (S/N R38 was run in fatigue test; the area examined here was on the unflanged side adjacent to the raceway).

CONCLUSIONS:

1. Ion implantation of the species and dosage levels evaluated herein were found not to be detrimental to fatigue endurance life.
2. Failure in all cases was due to fatigue spalling. Ion implantation did not effect the characteristics of the fatigue spalling.
3. The ion implantation process does not effect the bulk metallurgy (microstructure) of AISI M-50 steel.
4. The residual stresses on implanted and on unimplanted test specimens are not significantly different.
5. The ion implantation did not effect the dimensions of the test bearings within measurable limits.

REFERENCES

1. Private conversation with Gary Kuhlman, Naval Air Rework Facility, San Diego, California
2. L.G. Johnson, "The Statistical Treatment of Fatigue Experiments", Elsevier Publishing Company, 1964
3. J.H. Rumbarger, M.F. Jaskowiak, and R.A. Pallini
"GENROL - General Rolling Element Analysis Program",
Franklin Institute Research Laboratories Technical Report,
December, 1978

TABLE - 1
MEASUREMENT DATA (inches)

S/N	<u>BORE</u>		<u>O.D.</u>		<u>RADIAL CLEARANCE</u>		<u>WIDTH</u>		INNER CHANNEL
	<u>BEFORE</u>	<u>AFTER</u>	<u>BEFORE</u>	<u>AFTER</u>	<u>BEFORE</u>	<u>AFTER</u>	<u>INNER</u>	<u>OUTER</u>	
R1	1.5747	1.5747	2.67703	2.6770	.0020	.0019	.5901	.5900	.2770
R2	1.5747	1.5747	2.67715	2.67715	.0020	.0020	.5900	.5900	.2770
R3	1.57473	1.57465	2.6771	2.67705	.0019	.0019	.5904	.5900	.2770
R4	1.5747	1.5747	2.6771	2.67705	.0017	.0016	.5899	.5899	.2770
R5	1.57473	1.57467	2.67703	2.67695	.0016	.0015	.5901	.5900	.2768
R6	1.5747	1.57463	2.67713	2.6771	.0020	.0019	.5901	.5899	.2768
R7	1.5747	1.57464	2.67703	2.6770	.0018	.0018	.5904	.5898	.2770
R8	1.57465	1.57465	2.6771	2.6771	.0018	.0017	.5899	.5899	.2770
R9	1.57465	1.5747	2.67705	2.67702	.0020	.0019	.5898	.5898	.2770
R10	1.5747	1.5747	2.6771	2.6771	.0020	.0020	.5900	.5901	.2770
R11	1.57468	1.57463	2.67698	2.67698	.0018	.0017	.5903	.5898	.2770
R12	1.5747	1.5747	2.6771	2.67715	.0020	.0020	.5904	.5898	.2770
R13	1.57465	1.5747	2.6771	2.67707	.0019	.0018	.5898	.5900	.2770
R14	1.5747	1.5747	2.67693	2.6769	.0020	.0019	.5901	.5900	.2770
R15	1.5747	1.57465	2.67715	2.67715	.0017	.0016	.5901	.5898	.2770
R16	1.57473	1.57465	2.6771	2.67705	.0016	.0015	.5901	.5900	.2768
R17	1.5747		2.67695		.0018		.5901	.5899	.2768
R18	1.5747	1.57465	2.67695	2.6770	.0017	.0016	.5901	.5900	.2768
R20	1.57473	1.57465	2.67705	2.67708	.0017	.0016	.5901	.5897	.2770
R22	1.57473		2.6771		.0019		.5899	.5899	.2772
R23	1.5747		2.67715		.0018		.5903	.5899	.2770
R24	1.5747		2.6771		.0018		.5902	.5899	.2770
R26	1.5747		2.67705		.0020		.5902	.5899	.2770
R28	1.5747		2.6771		.0020		.5902	.5899	.2768
R29	1.5747		2.6771		.0019		.5899	.5900	.2770
R30	1.5747		2.6771		.0019		.5901	.5901	.2768
R31	1.57473		2.67715		.0019		.5903	.5900	.2770
R32	1.5747		2.6771		.0019		.5900	.5899	.2770
R33	1.5747		2.6771		.0018		.5900	.5899	.2770
R34	1.57473		2.67708		.0018		.5904	.5901	.2770
R36	1.57468		2.67705		.0019		.5903	.5899	.2770
R38	1.57468	1.5747	2.67715	2.6771	.0018	.0018	.5899	.5899	.2768
R39	1.57465	1.5747	2.67715	2.6771	.0018	.0018	.5903	.5898	.2768

TABLE - 1 Continued
MEASUREMENT DATA

S/N	SURFACE FINISH (microinches)						HARDNESS (ROCKWELL C)			
	INNER RACE		OUTER RACE		INNER LAND		INNER RING		OUTER RING	
	BEFORE	AFTER	BEFORE	AFTER	BEFORE	AFTER	BEFORE	AFTER	BEFORE	AFTER
R1	5	4	4	3	6	6.5	62.5	63.2	64	63.8
R2	3	3	4	3.5	7	7	62.5	63.5	63	62
R3	4	5	4	4.5	6	7	63	62.8	63	63.2
R4	5	5.5	4	4	6	6	63	63.5	64	63.8
R5	5	6	4	5	6	6	63	63	64	63.8
R6	4	5	4	5	7	6.5	62.5	63.2	63	63
R7	4	4	3	3.5	7	5	62.5	63	64	64
R8	4	4.5	4	4.5	6	6	63	63	64	63
R9	4	4.5	3	3.5	6	6.5	62.5	63	64	63.2
R10	5	5.5	4	3	6	7	62.5	63	64	64.2
R11	5	6	5	5.5	5	6	63	63	63	63.2
R12	6	7	4	3.5	6	6	62.5	63.2	63	63.5
R13	5	5.5	4	5	6	7	63	63.5	64	64
R14	5	4.5	3	3.5	5	6	63	63.2	64	63.5
R15	5	5.5	4	4	6	5.5	63	63	64	63.2
R16	4	4.5	4	3.5	6	5	62.5	63.5	64	63.5
R17	5	-	4	-	6	-	63	-	64	-
R18	5	6	4	4	7	7	62	63	63	63
R20	5	5.5	5	5	6	7	63	63.5	64	63.8
R22	4		4		5		62.5		64	
R23	4		5		6		63		64	
R24	5		4		6		63		64	
R26	5		4		7		63		63	
R28	4		4		5		62.5		64	
R29	5		5		5		63		64	
R30	4		3		6		63		64	
R31	4		4		7		62.5		63	
R32	4		3		6		62.2		64	
R33	5		4		5		62		64	
R34	5		4		6		62		63.8	
R36	4		3		6		62.5		63	
R38	5	5.5	5	5.5	5	5	63	63.5	64	64
R39	5	6	4	4.5	5	6	62.5	63.2	63	64

TABLE - 2
MEASUREMENT DATA
ROLLERS

DIAMETER	- 0.276175 - 0.2762 inch	Before and after implantation
LENGTH	- 0.2756 - 0.2758 inch	Before and after implantation
FLAT LENGTH	- 0.0920 - 0.1720 inch	Specified; sample varied from 0.110 - 0.150 inch
CORNER BREAKOUT	- 0.015 - 0.020 inch	
CROWN DIAMETER	- 30 inches, nominal	
SURFACE FINISH	- 1.5 to 3 microinches, before and after implantation	
HARDNESS	- 61.7 to 62.7 Rockwell C	(Sample)
ROUNDNESS (two point)	- within 0.000010 inch	

Two bearings were assembled with rollers from a different lot of VIM-VAR M-50 rollers and put into test for comparison purposes. These rollers had the following geometry:

DIAMETER	- 0.27605 - 0.276075 inch
LENGTH	- 0.2754 - 0.2756 inch
FLAT LENGTH	- 0.1280 - 0.1670 inch
CROWN RADIUS	- 15.5 inches, nominal
HARDNESS	- 61.6 to 62.7 Rockwell C (Sample)

TABLE ~ 3
RESIDUAL STRESS MEASUREMENTS (K psi)

DISTANCE BELOW SURFACE (INCH)	OUTER RACES			INNER RACES			ROLLERS		
	S/N R37 REFERENCE	S/N R17 IMPLANTED	S/N R37 REFERENCE	S/N R17 IMPLANTED	S/N R37 REFERENCE	S/N R17 IMPLANTED	NEW	CHROMIUM IMPLANTED	CHROMIUM + PHOSPHORUS IMPLANTED
SURFACE	-106.1	-85.9	-106.5	-76.4	-181.6	-179.1	-148.3		
.0002	-49.6	-43.2	-26.4	-29.3	-45.1	-85.9	-65.0		
.0004	-	-27.9	-11.2	-8.9	-30.7	-41.6	-29.2		
.003	+12.5	+12.5	+18.7	-6.2	+6.4	-	-12.2		
.005	+24.2	+17.2	+14.9	+4.1	+0.2	+10.1	+4.3		
.007	+21.0	+1.2	+18.2	-3.7	+11.1	+8.4	+3.2		

TABLE 4

FATIGUE ENDURANCE LIVES

<u>S/N</u>	<u>GROUP</u>	<u>MACHINE</u>	<u>POSITION</u>	<u>HOURS</u>	<u>STATUS</u>
R1	Cr+P	A-9	3	351.8	No failure
R2	Cr+P	A-9	2	100.1	Spalled Roller
R3	Cr+P	A-10	3	93.0	Spalled Roller
R4	Cr+P	A-11	1	191.4	Spalled Roller
R5	Cr+P	A-11	4	81.7	Spalled Roller
R6	Cr+P	A-12	1	361.2	Spalled Roller
R7	Cr+P	A-11, 12	3	420.4	No Failure
R8	Cr+P	A-12	2	191.7	Spalled Roller
R9	Cr+P	A-12	2	278.4	Spalled Roller
R10	Cr+P	A-9	1	92.6	Spalled Rollers (2)
R11	Cr	A-10, 9	1	150.9	Spalled Roller
R12	Cr	A-9	3	135.1	Spalled Roller
R13	Cr	A-10, 9	4	399.3	Spalled Roller
R14	Cr	A-12	3	127.4	Spalled Roller
R15	Cr	A-12	1	306.9	No failure
R16	Cr	A-11	1	132.8	Spalled Roller
R18	Cr	A-12	3	94.4	Spalled Roller
R20	Cr	A-11, 12	4	193.4	Spalled Rollers (2)
R38	Cr	A-11	2	36.2	Spalled Rollers and Inner
R39	Cr	A-10	3	252.2	Spalled Roller
R22	Ref	A-10	1	177.6	Spalled Roller
R23	Ref	A-11	3	76.2	Spalled Roller
R24	Ref	A-12, 10	3	177.9	Spalled Roller
R26	Ref	A-9	4	383.8	Spalled Roller
R28	Ref	A-9	1	394.3	No failure
R29	Ref	A-10	2	296.8	Spalled Roller
R30	Ref	A-11	2	86.9	Spalled Roller
R31	Ref	A-9	2	113.2	Spalled Roller
R32	Ref	A-9	2	221.9	Spalled Roller
R36	Ref	A-12	4	361.4	No failure
R33	Ref*	A-11	2	78.0	Spalled Roller
R34	Ref*	A-10, 12	3	215.9	Spalled Roller

* THESE BEARINGS HAVE ROLLERS FROM A SECOND LOT

MATERIAL:

RINGS: VIM-VAR M-50
TOOL STEEL

ROLLERS: VIM-VAR M-50
TOOL STEEL

CAGE: SILICON-IRON-
BRONZE, SILVER
PLATED .0005 in.
to .0020 in.
PER AMS 2412

PREC 5 TOLERANCES

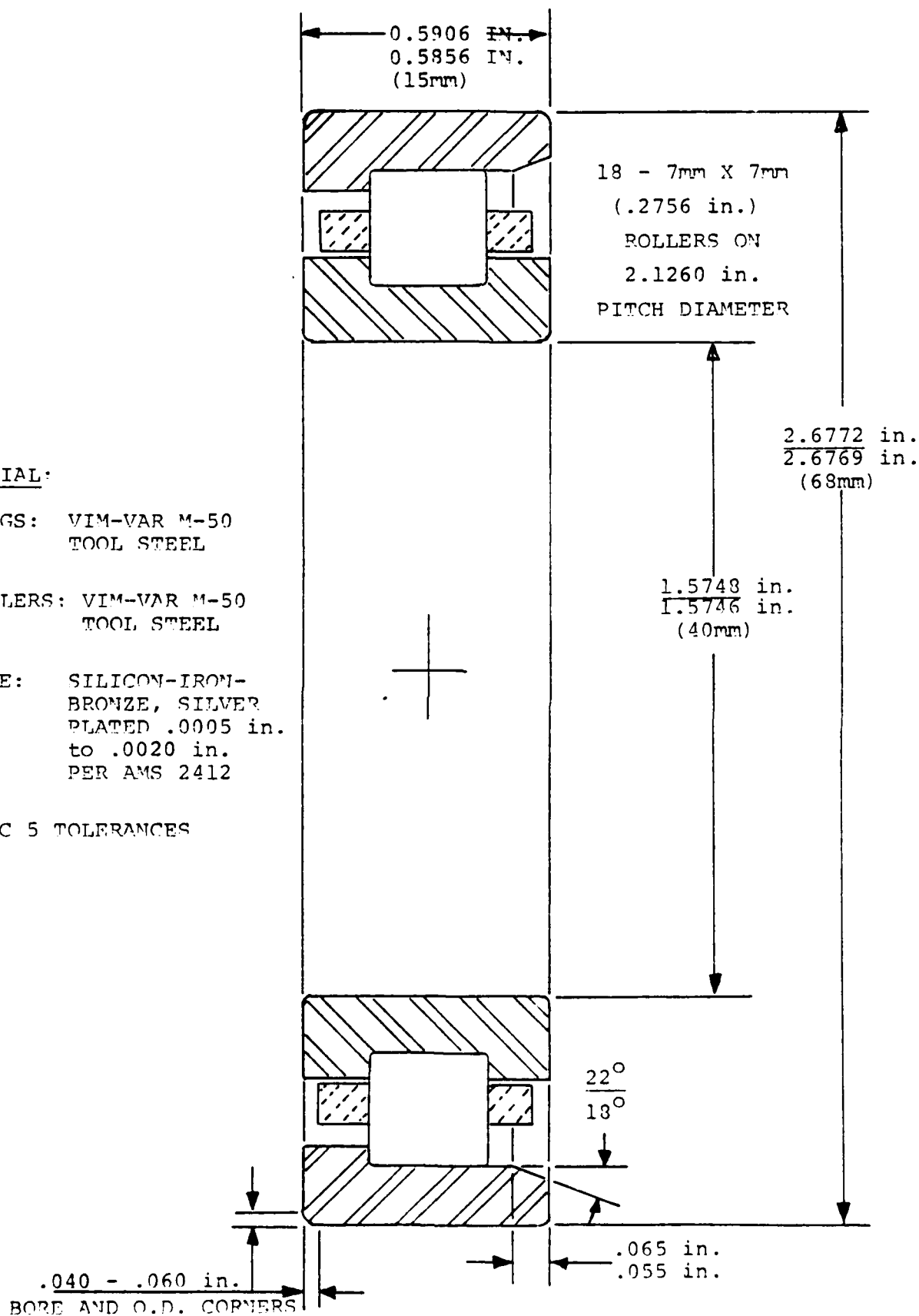


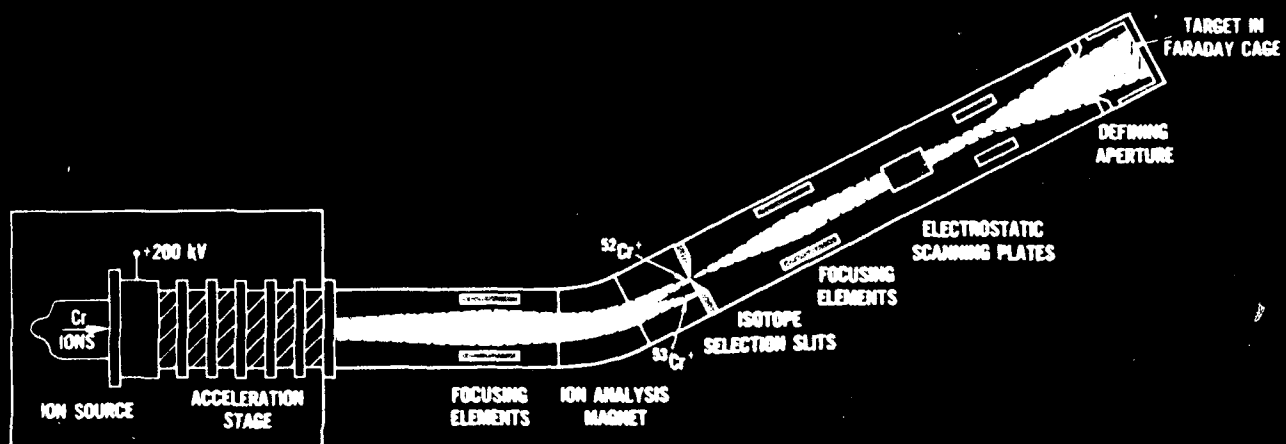
FIGURE 1 - MPC R108KD-7 ROLLER BEARING

ION IMPLANTATION PARAMETERS

IMPLANTED ELEMENTS	- VIRTUALLY ANY ELEMENT FROM HYDROGEN TO URANIUM CAN BE IMPLANTED.
ION ENERGIES	- NORMALLY 2 TO 200 KeV. ENERGIES UP TO 5 MeV MAY BE OBTAINED WITH THE VAN DE GRAAFF ACCELERATOR.
ION RANGES	- VARY WITH ION ENERGY, ION SPECIES AND HOST MATERIAL. RANGES NORMALLY 0.01 μm to 1.0 μm .
RANGE DISTRIBUTION	- APPROXIMATELY GAUSSIAN. CHOICE OF ENERGIES ALLOW TAILORED DEPTH DISTRIBUTION PROFILES.
CONCENTRATION	- FROM TRACE AMOUNTS UP TO 50% OR MORE.
HOST MATERIAL	- ANY SOLID MATERIAL CAN BE IMPLANTED.
SPECIAL EFFECTS	- SPUTTERING, RADIATION DAMAGE, RADIATION ENHANCED DIFFUSION.

Figure 2 - The effect produced by ion implantation depends on a number of parameters. These parameters, together with typical ranges of values, are shown here.

ION IMPLANTATION SYSTEM



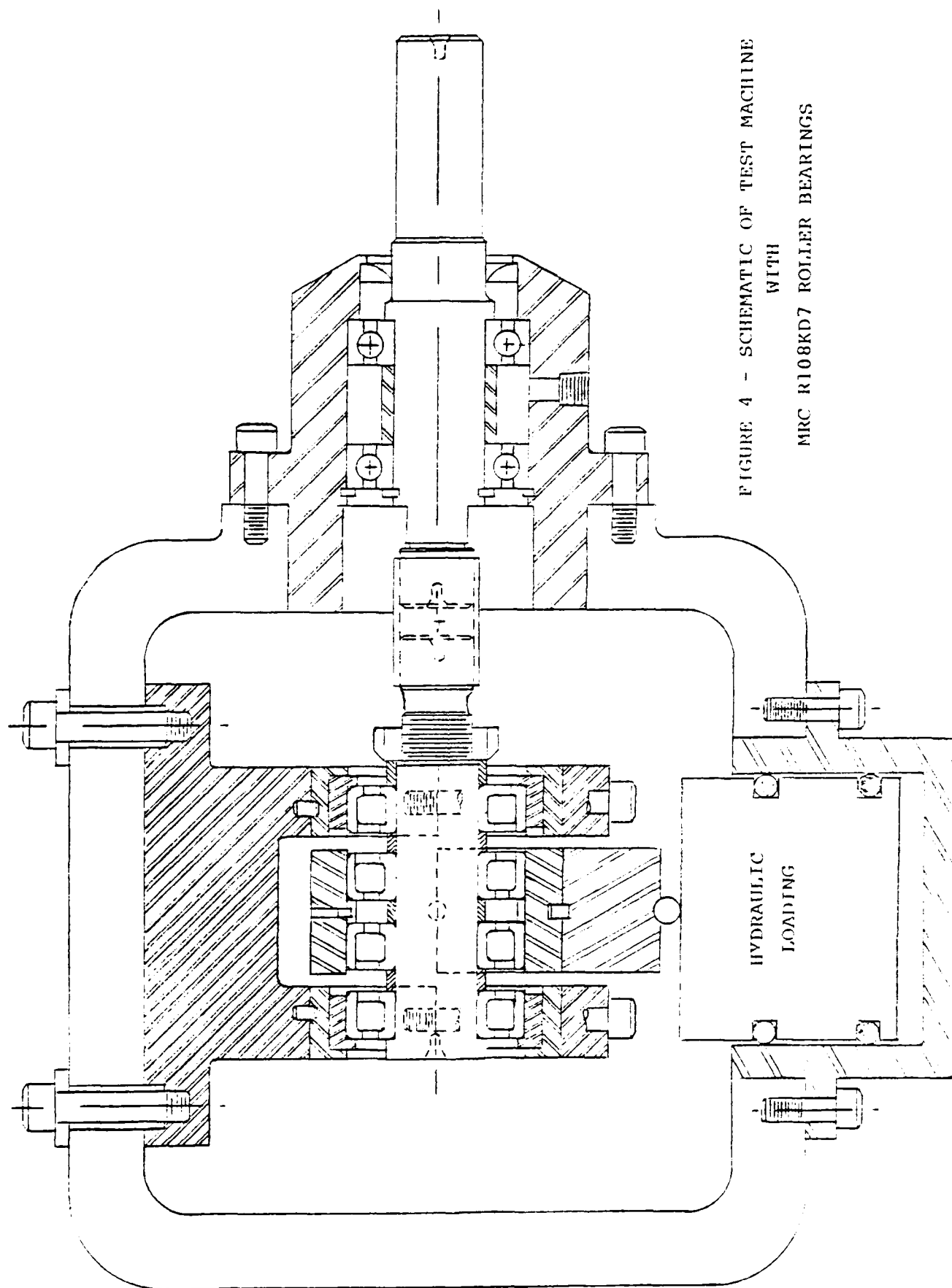


FIGURE 4 - SCHEMATIC OF TEST MACHINE
WITH
MRC R108KD7 ROLLER BEARINGS

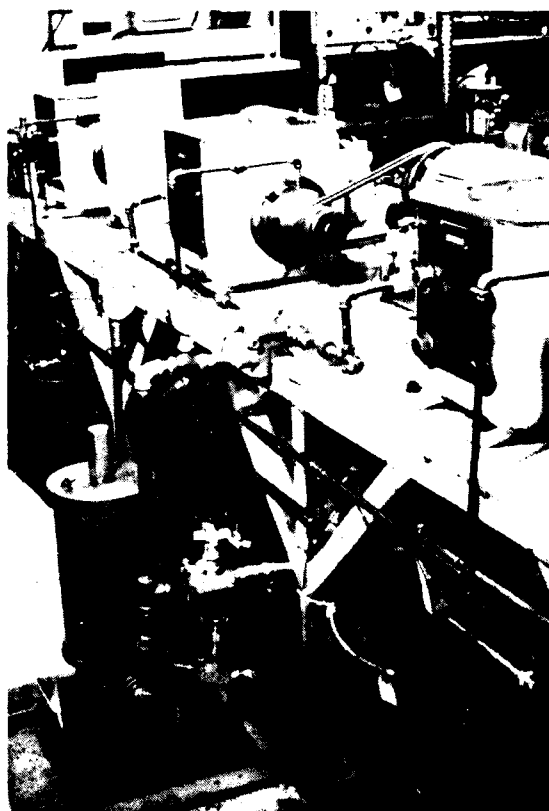


FIGURE 5 - BATTERY OF MACHINES USED
FOR FATIGUE ENDURANCE TESTING

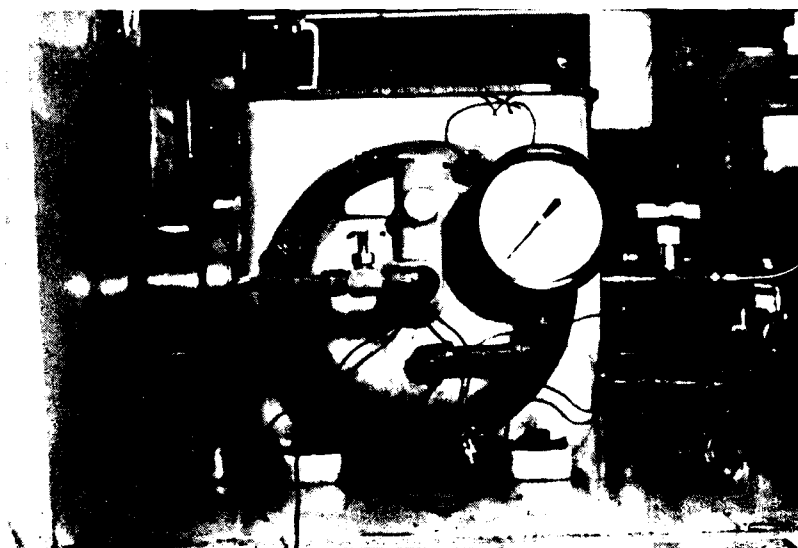
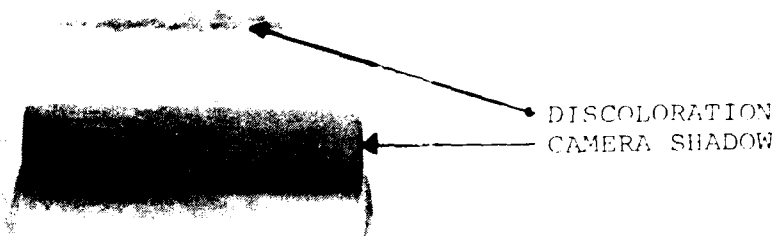
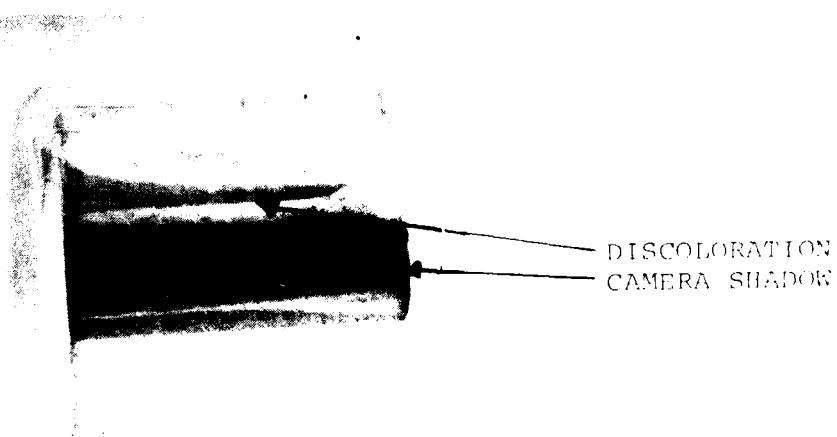


FIGURE 6 - FATIGUE ENDURANCE TEST MACHINE



DISCOLORATION
CAMERA SHADOW



DISCOLORATION
CAMERA SHADOW

FIGURE 7 - 10" IMPLANTED ROLLERS WITH DISCOLORED AREAS

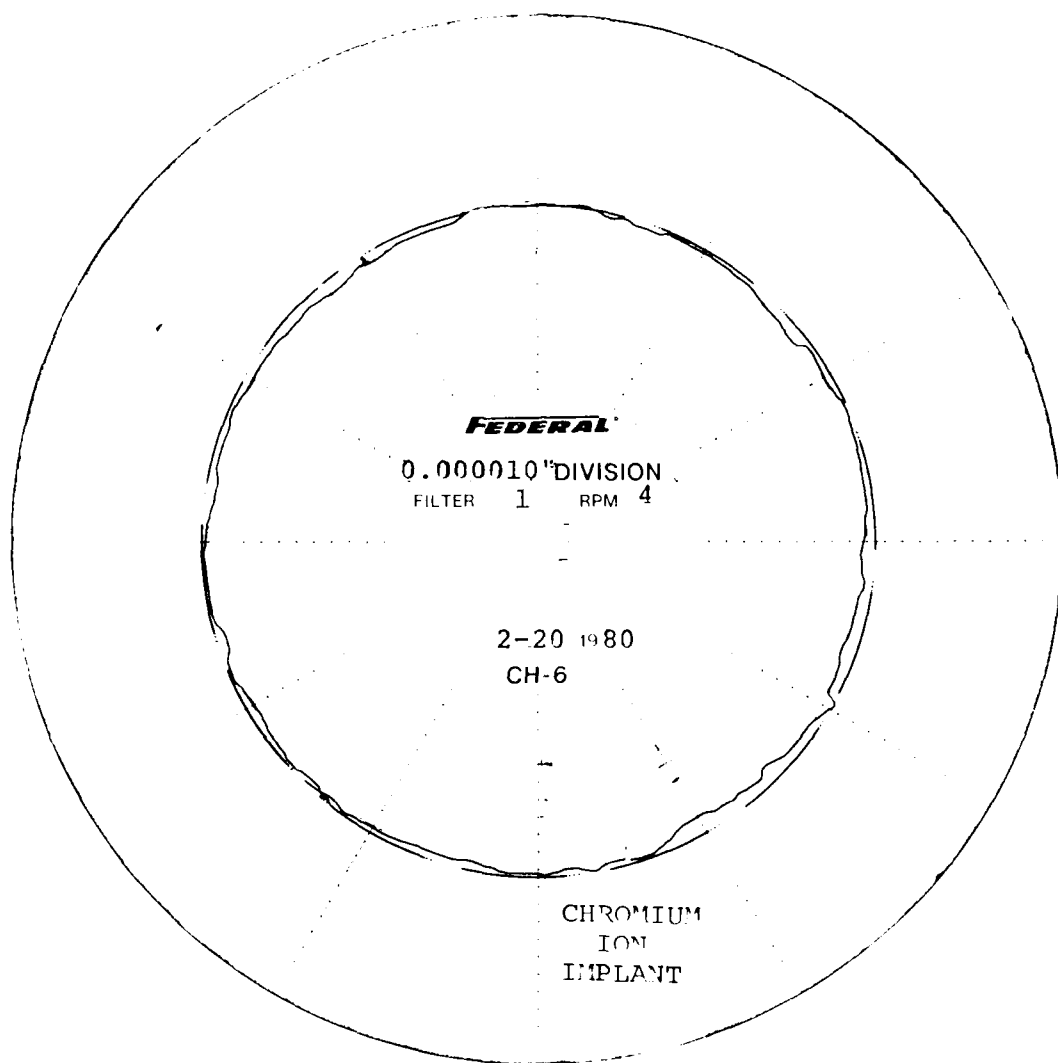
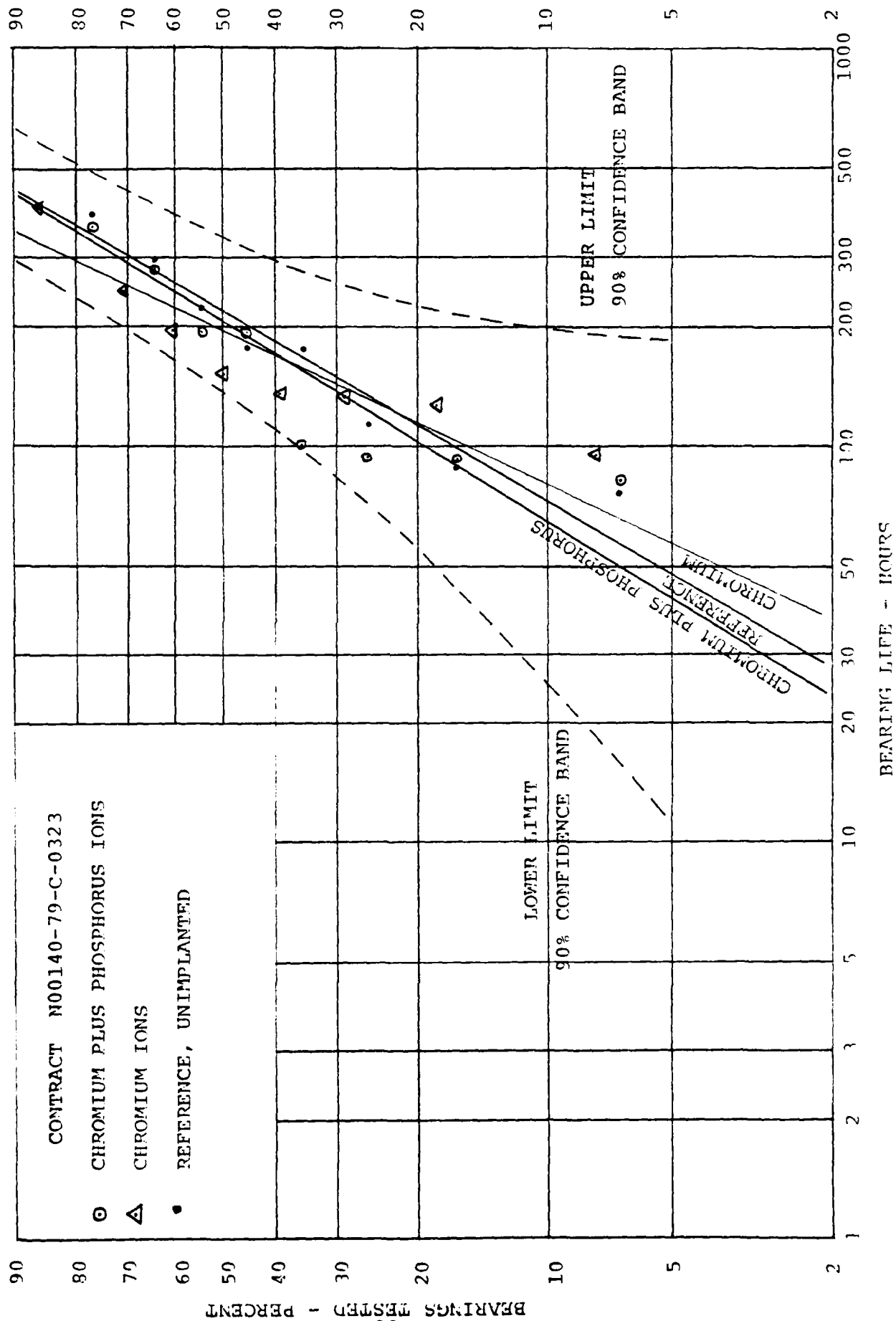
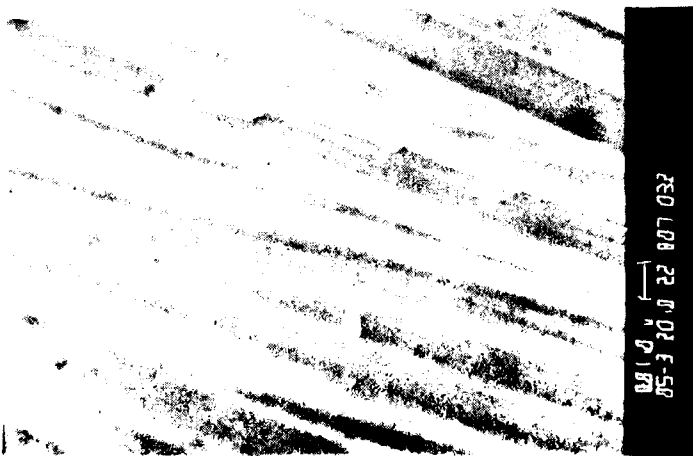


FIGURE 8 - CIRCUMFERENTIAL PROFILE TRACE OF TYPICAL ROLLER
(THIS ROLLER WAS ION IMPLANTED AND HAD DISTINCT DISCOLORED BAND)

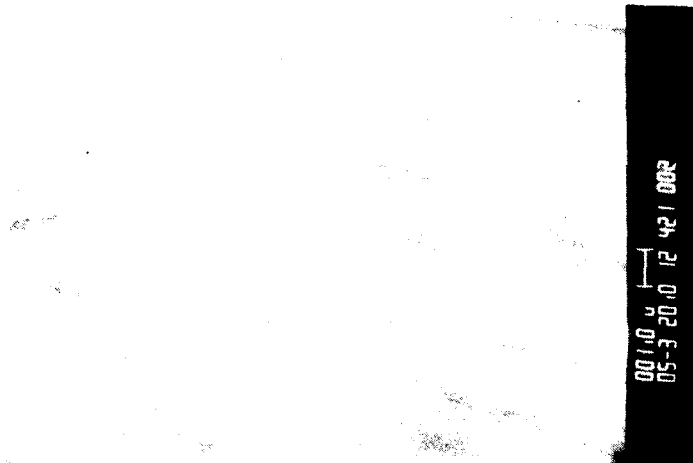
FIGURE 9 - FATIGUE ENDURANCE OF ION IMPLANTED ROLLER BEARINGS





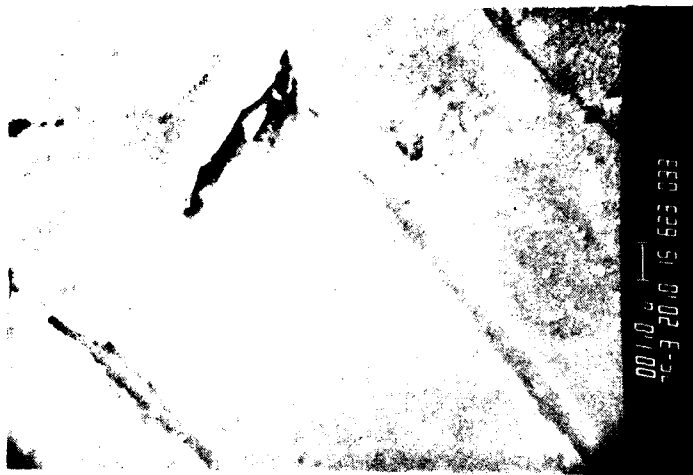
0010 4
05-3 10.0 22 807 032

BEFORE IMPLANTATION



0010 4
05-3 20.0 12 421 002

AFTER IMPLANTATION



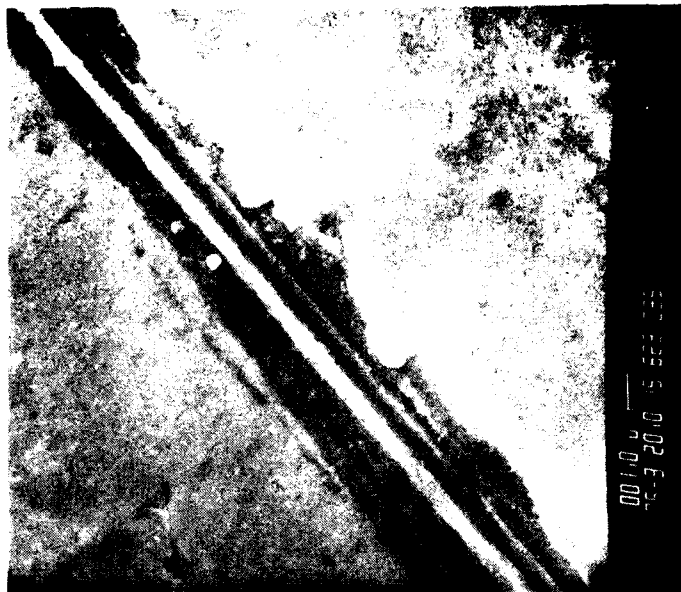
0010 4
05-3 20.0 15 665 033

AFTER TEST

FIGURE 10 - SEM PHOTOS OF INNER RACE OF S/N R8.
RACEWAY WAS IMPLANTED WITH CHROMIUM
PLUS PHOSPHORUS. MAGNIFICATION 4700X



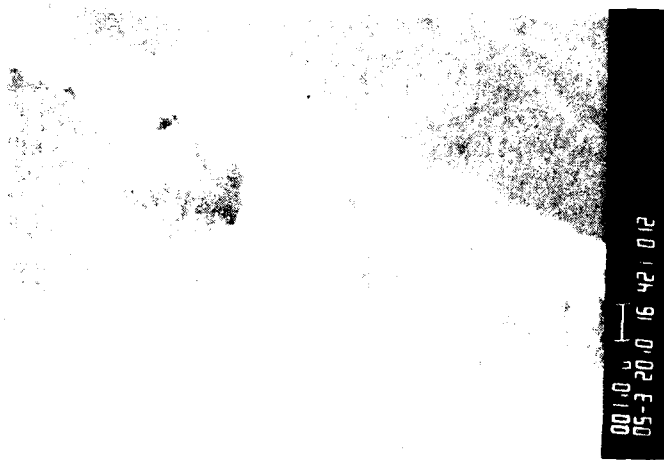
AFTER IMPLANTATION



AFTER TEST

FIGURE 11 - SEM PHOTOS OF INNER RACE OF S/N R18.
RACEWAY WAS IMPLANTED WITH CHROMIUM IONS
MAGNIFICATION 4700X

001.0 05-3 20.0 16 823 002



001.0 05-3 20.0 16 421 012

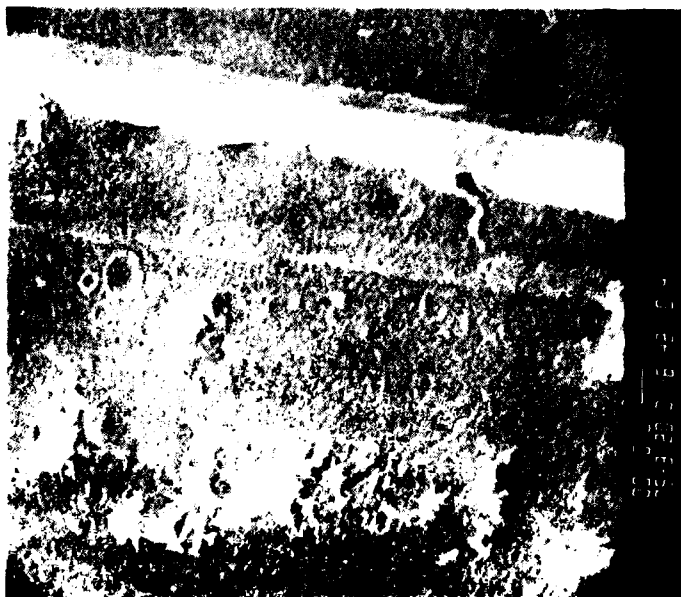
AFTER IMPLANTATION



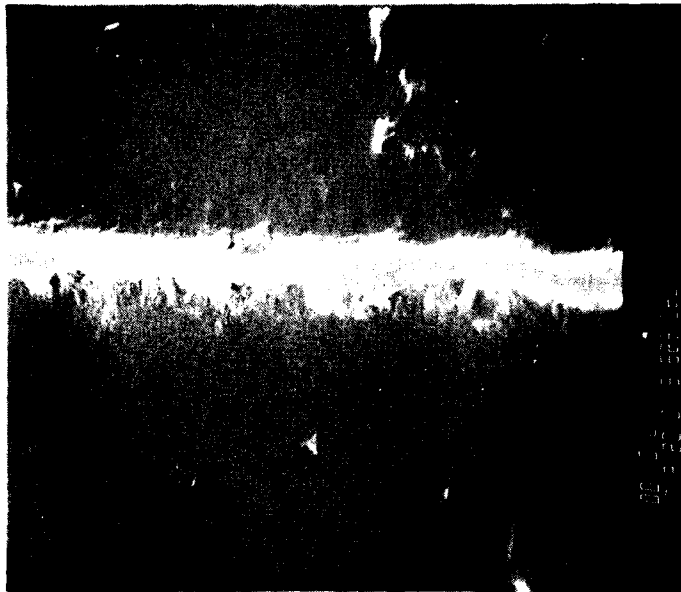
001.0 05-3 20.0 16 523 018

AFTER TEST

FIGURE 12 - 20X PHOTO OF REPLICATION OF OUTER ENFACE OF S/N P8.
NO HONEY WAS IMPLANTED WITH CHROMIUM PLUS PHOSPHORUS
ON 05-3 20.0 16 523 018



A) AFTER IMPLANTATION

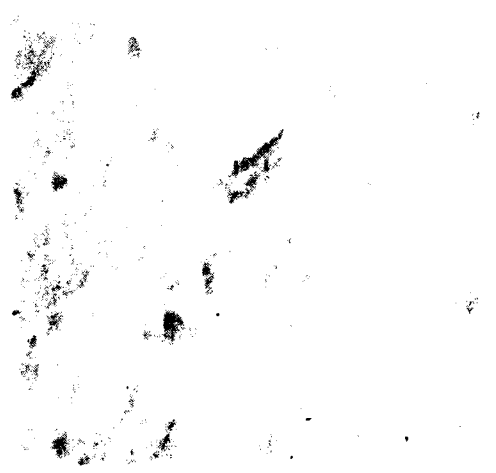


B) AFTER TEST

FIGURE 13 - SEM PHOTOS OF REPLICAS OF OUTER RACE OF S/N R18, SHOWING GRINDING FURROW NEAR CENTER OF RACE, MOTTLED APPEARANCE ON PHOTOGRAPH "A" DUE TO FOREIGN MATERIAL. RACEWAY WAS IMPLANTED WITH CHROMIUM IONS. MAGNIFICATION 4700X



00100 1 2 0102 E-50
05-3 20 0 21 623 038



00100 1 2 0102 E-50
05-3 20 0 21 623 038



00100 1 2 0102 E-50
05-3 20 0 21 623 038

FIGURE 15

RESIDUAL STRESS MEASUREMENTS

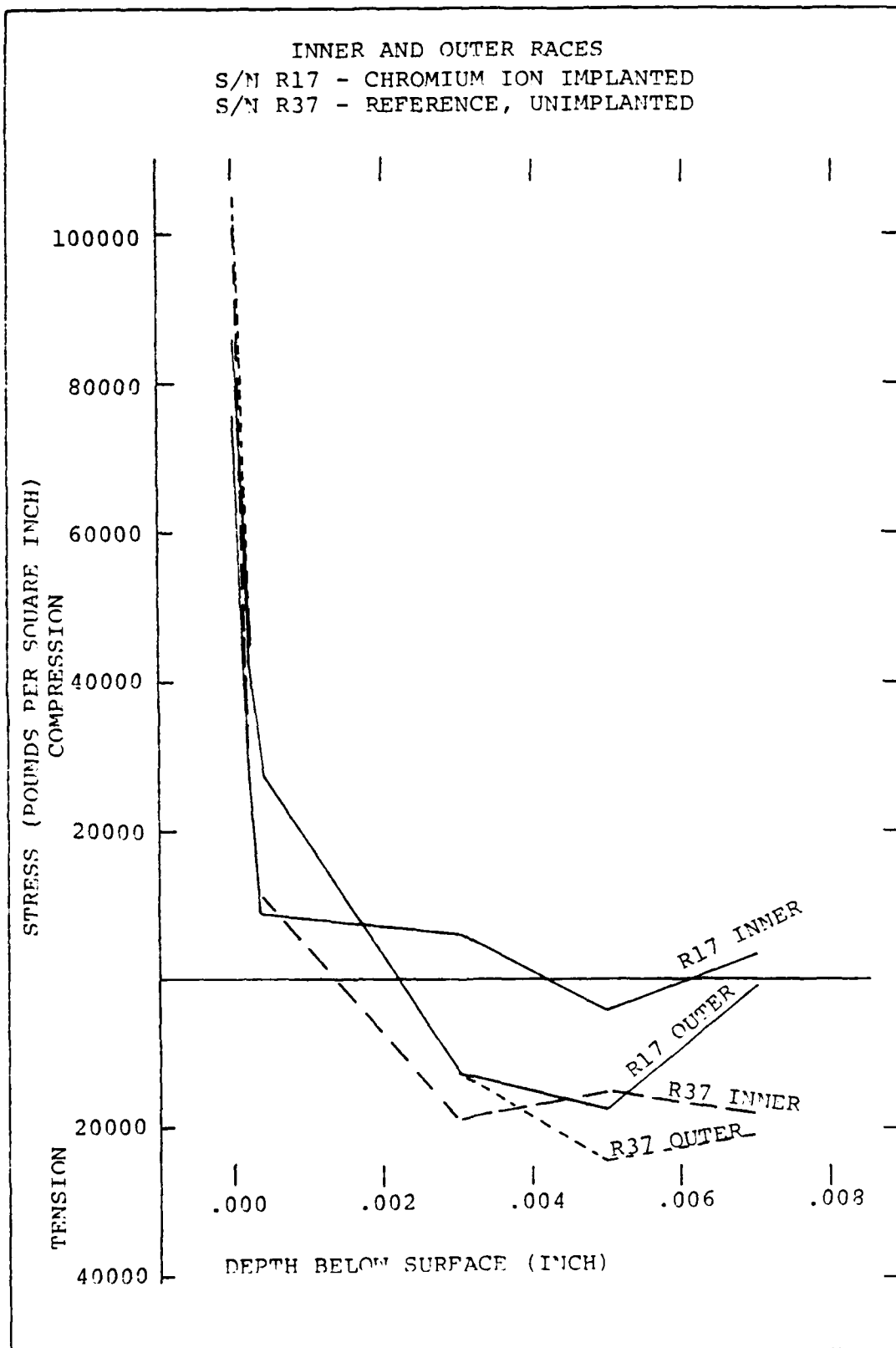
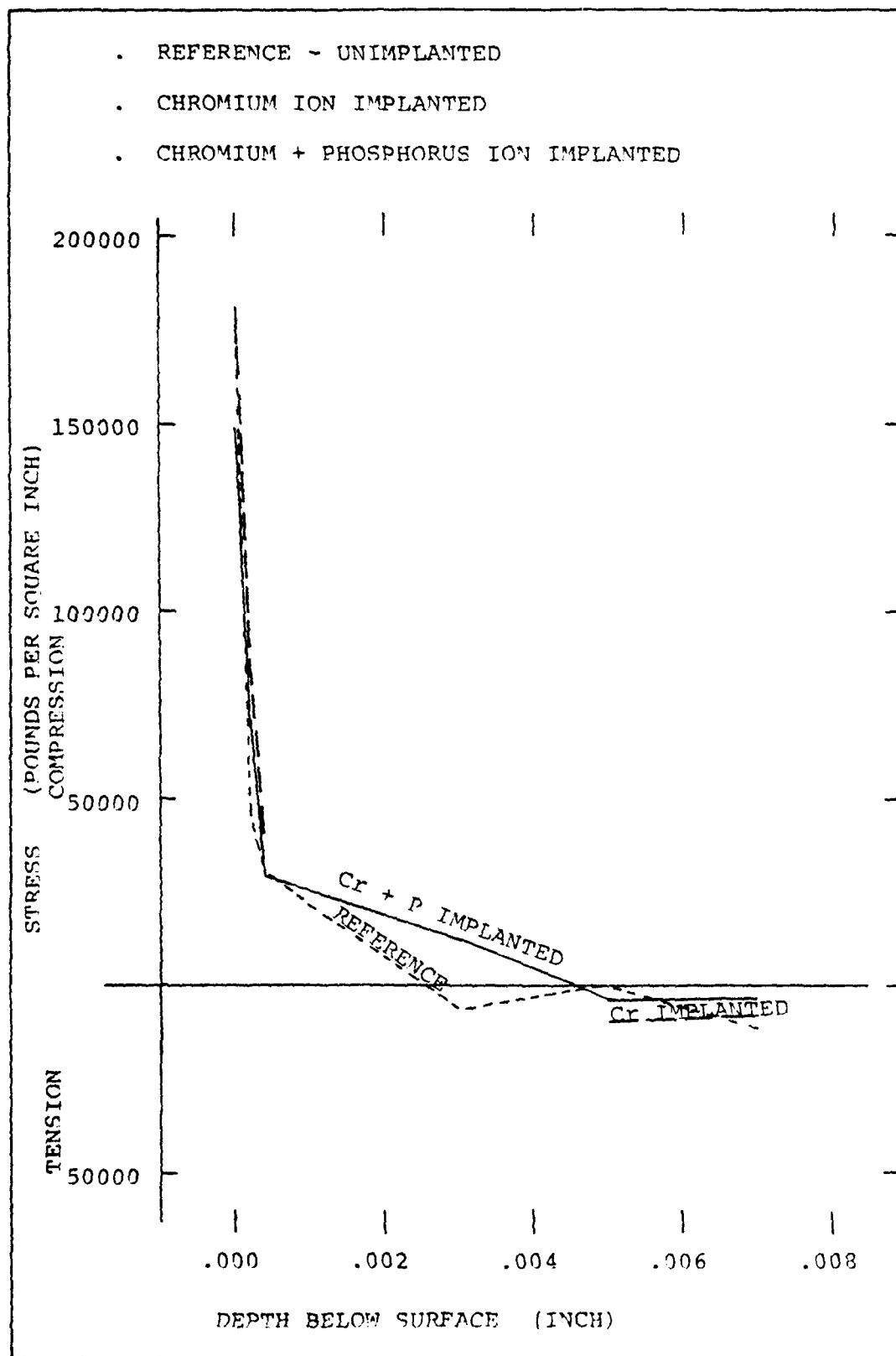
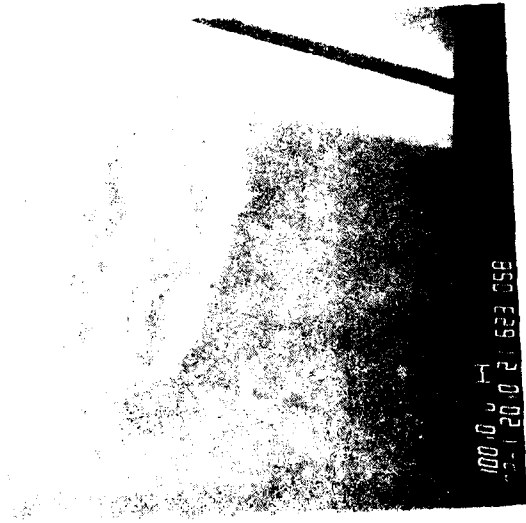


FIGURE 16

RESIDUAL STRESS MEASUREMENTS 7x7mm ROLLERS

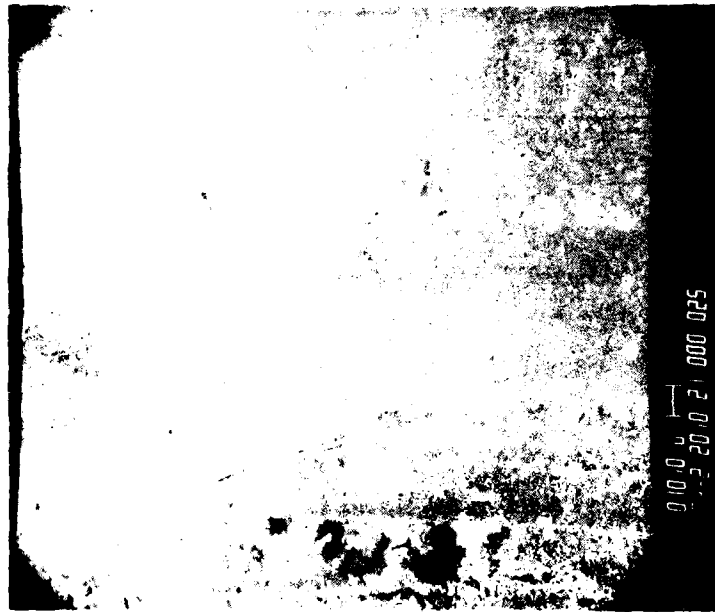




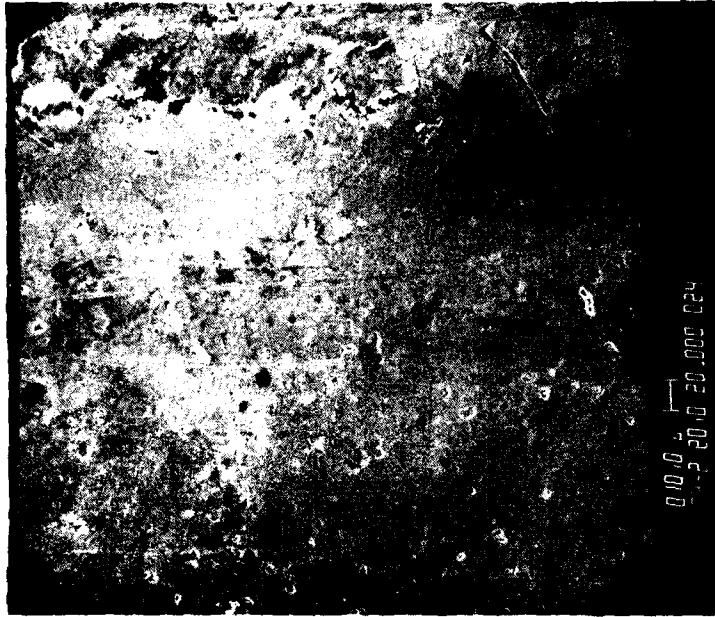
100.0 1/4 H
-3-120.0 21 623 056



100.0 20.0 21.623 045



CORNER



CORNER

FIGURE 19 - SEM PHOTOS OF AREA ADJACENT TO CORNERS ON A ROLLER FROM S/N R7. MAGNIFICATION 400X. THIS BEARING RAN 420 HOURS WITHOUT FAILURE BUT ROLLERS WERE HIGHLY BURNISHED NEAR CORNERS.

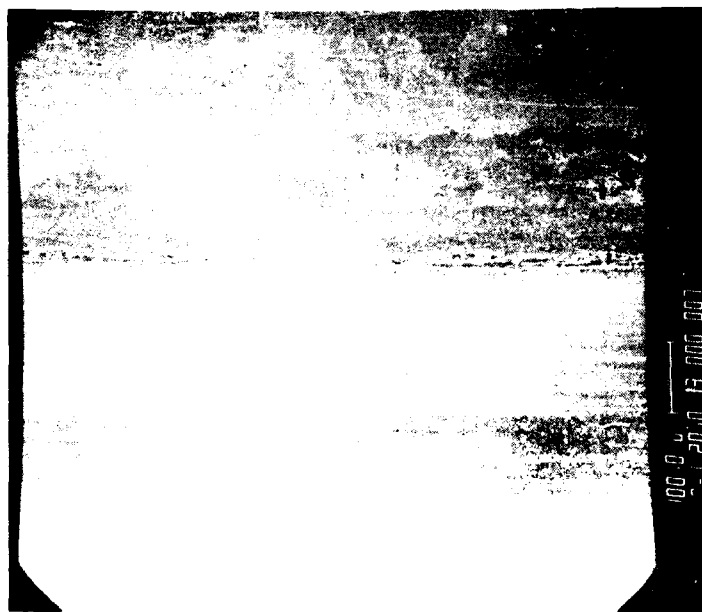
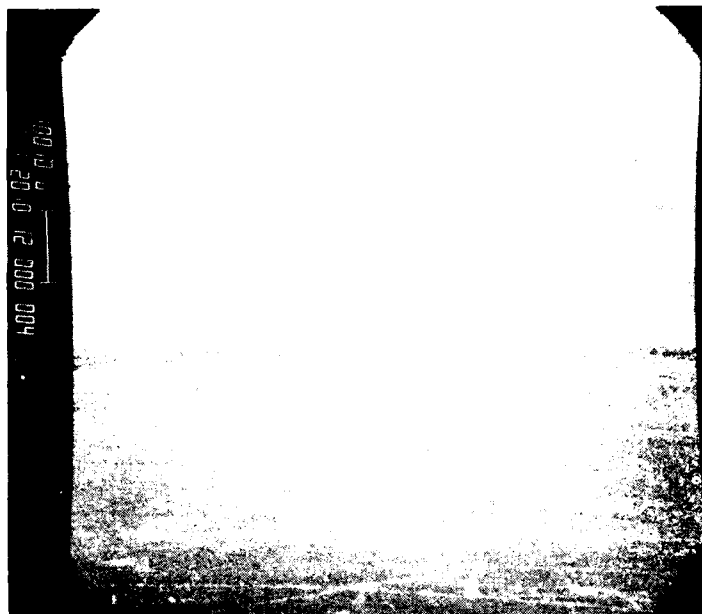
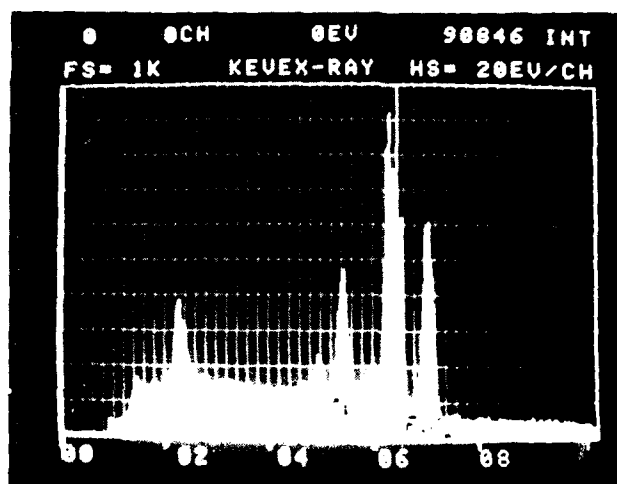


FIGURE 21 - SEM PHOTOS OF INNER BEARING SURFACE, FIG. 21 F7.
 MAGNIFICATION: 100X. BEARING APPLIC. LOW-ANGLE RING FLANGES
 WHICH ARE OUT OF FOCUS. BEARING IN FOCUS BEARING
 WERE RUBNISHED ON BOTH SIDES.

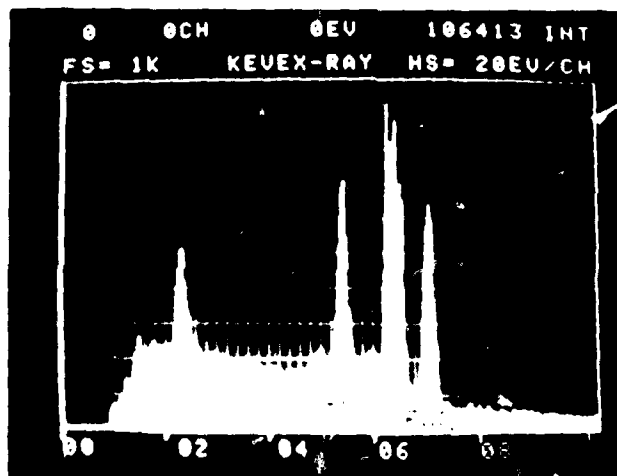


Figure 22 - A photograph of the same area as Figure 21, but with a different exposure. The image is very dark and noisy, with a vertical ruler on the right side showing markings from 0 to 200. The text is mostly illegible due to the poor quality of the scan.

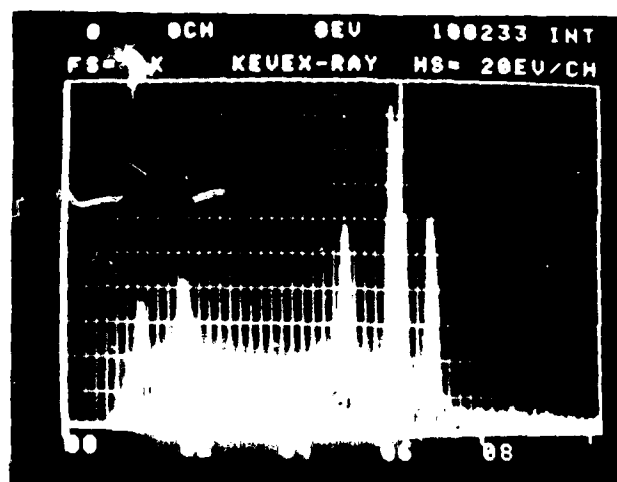
NO IMPLANTATION



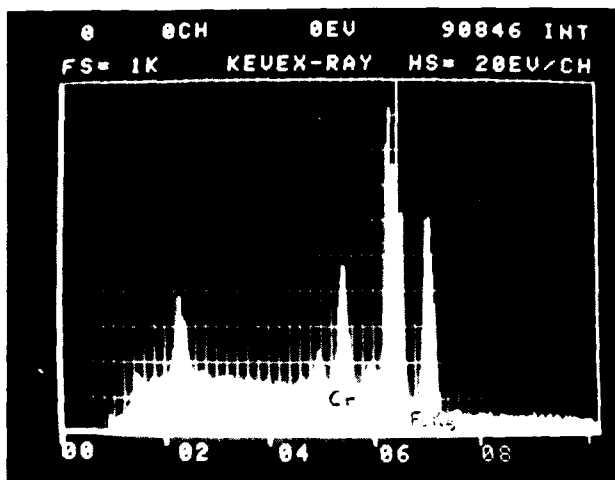
AS IMPLANTED



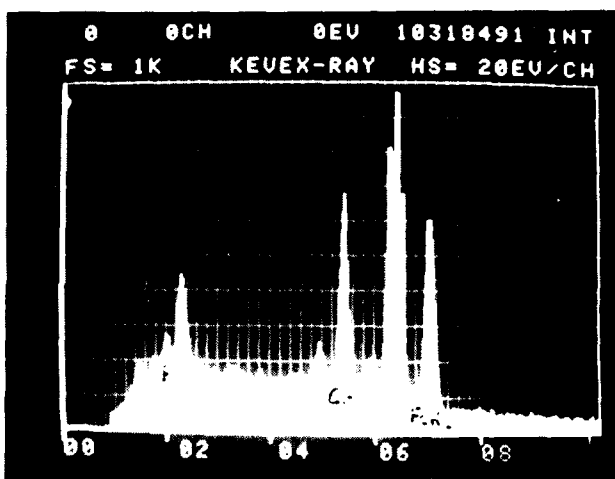
ROLLER USED IN
S/N R20



NO IMPLANTATION



AS IMPLANTED



ROLLER USED IN
S/N R7

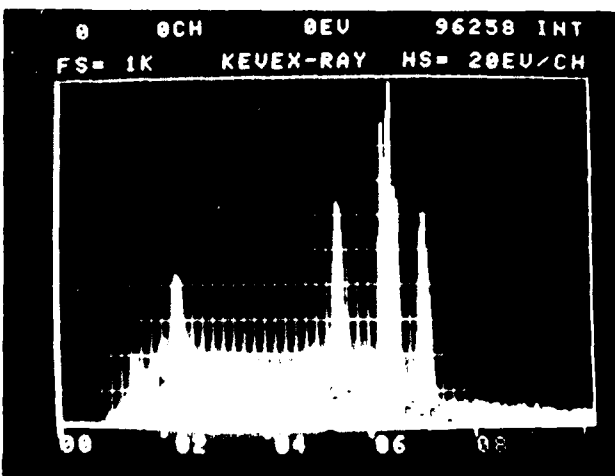
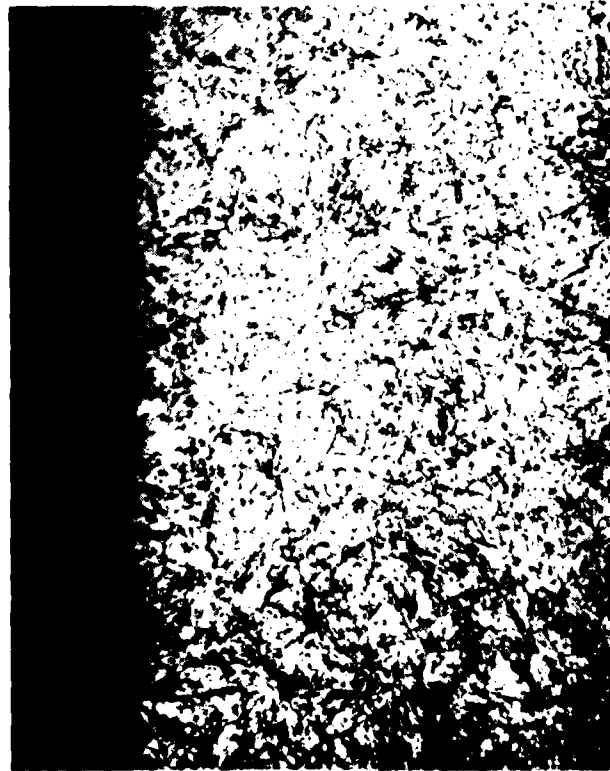


FIGURE 24 - SURFACE CHEMISTRY OF ROLLER USED IN S/N R7
CHROMIUM PEAK AT 88.5 eV, IRON PEAK AT 87.5 eV



a) TEMPERATURE 1000°C, 100X, 1000X



b) OUTER SPACE FROM 1000°C, 100X, 1000X

FIGURE 25 - TEMPERATURE OF MICROSTRUCTURE OF
TEMPERATURE OF IMPLANTED PARTS

HULLING ELEMENT BEARING ANALYSIS PROGRAM (5 DEGREES OF FREEDOM)

HULLER BEARING ANALYSIS - H108KD7 - RESEARCH

INPUT DATA FOR INDIVIDUAL BEARINGS

BEARING NO.	TYPE OF BEARING	NUMBER OF ELEMENTS	ELEMENT DIAMETER	PITCH DIAMETER	CONTACT ANGLE	RACE CURVATURES	DIAMETRAL CLEARANCE	BEARING LOCATION
1	CYL	18	2.7620E-01	2.1260E 00	0.0	OUTER 0.0 INNER 0.0	1.5000E-03	0.0
2	HOLL LENGTH	MODULUS OF ELASTICITY	HOLL CYL. LENGTH	POISSON'S RATIO	FATIGUE CONSTANT	VALUES OF LAMBDA		
3	2.4000E-01	2.9000E 07	2.9000E 07	2.5000E-01	4.9500E 04	OUTER 6.6000E-01 INNER 6.6000E-01		
4	INITIAL DISPLACEMENTS AT BEARING CENTER	ABOUT X	ABOUT Y	ABOUT Z	ABOUT X	ABOUT Y	ABOUT Z	PHASE ANGLE
5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
6	WET HULL SLOPE	LOAD-LIFE EXPONENT	AXIAL FLOW	RADIAL FLOW	ETA (DEG)	AXIAL PRELOAD	PRELOAD DEFLECTION	CONTACT ANG.
7	1.1250E 00	3.3333E 00	NO	NO	0.0	0.0	0.0	0.0
8	CAGE OPENING	AXIAL SPRING	HOLL CYL. LENGTH	CROWN	HALL EXP.	CONE RIB DIA. (IN)	SHOULDER CLEARANCE	SHOULDER HEIGHT (IN)
9	0.0	NO	9.2000E-02	3.0270E 01	0.0	0.0	0.0	0.0
10	1 HAS 18 ELEMENTS AND WAS MODELED WITH 18 ELEMENTS							

INPUT DATA FOR BEARING SYSTEM

HPM (METATIVE)	ALONG X	ALONG Y	ALONG Z	ABOUT X	ABOUT Y	ABOUT Z
7.0000E 03	-2.8600E 03	0.0	0.0	0.0	0.0	0.0

INNER RACES ROTATE WITH RESPECT TO LOAD
OUTER RACES STATIONARY WITH RESPECT TO LOAD
PROBLEM IS POSED IN FOLLOWING DEGREES OF FREEDOM
ALONG X,

OUTPUT DATA FOR BEARING SYSTEM NUMBER OF ITERATIONS = 3

*** LIFE COMPUTED PER AFMA STANDARDS ***

HOURS LIFE (H-10) 1.4433E 01
 SYSTEM REACTIONS ON SHAFT AT ORIGIN
 ALONG X 2.8600E 03 1.6174E-03 0.0 ABOUT X 2.1370E-06 5.9709E-05
 ALONG Y 0.0 0.0 ABOUT Y 0.0 0.0
 ALONG Z 0.0 0.0

DISPLACEMENTS OF REFERENCE LINE AT ORIGIN
 ALONG X -2.0169E-03 0.0 ABOUT X 0.0
 ALONG Y 0.0 0.0 ABOUT Y 0.0
 ALONG Z 0.0 0.0

NON-LINEAR SPRING RATES OF SYSTEM AT ORIGIN
 DFX/DX 0.0 DFX/DY 0.0 DFX/DZ 0.0 DFX/DALX 0.0 DFX/DALY 0.0
 DFX/DZ 0.0 DFX/DY 0.0 DFX/DZ 0.0 DFX/DALX 0.0 DFX/DALY 0.0

NON-LINEAR SPRING RATES (CONTINUED)
 DFX/DX 0.0 DFX/DY 0.0 DFX/DZ 0.0 DFX/DALX 0.0 DFX/DALY 0.0
 DFX/DZ 0.0 DFX/DY 0.0 DFX/DZ 0.0 DFX/DALX 0.0 DFX/DALY 0.0

BEARING NO. 1
 REACTIONS OF BEARINGS ON SHAFT (H-10) LIFE
 ALONG X 2.8600E 03 1.6174E-03 0.0 ABOUT X 2.1370E-06 5.9709E-05
 ALONG Y 0.0 0.0 ABOUT Y 0.0 0.0
 ALONG Z 0.0 0.0

BEARING NO. 1
 RELATIVE SHAFT DISPLACEMENTS AT BEARING CENTER
 ALONG X -2.0169E-03 0.0 ABOUT X 0.0
 ALONG Y 0.0 0.0 ABOUT Y 0.0
 ALONG Z 0.0 0.0
 CAPACITY 5.6875E 03 (RADIAL) 3.3124E 03 EQUIV. LOAD 0.0

BEARING NO. 1
 PARTIAL DERIVATIVES OF BEARING REACTIONS WITH RESPECT TO DISPLACEMENTS AT SYSTEM ORIGIN
 DFX/DX 0.0 DFX/DY 0.0 DFX/DZ 0.0 DFX/DALX 0.0 DFX/DALY 0.0
 DFX/DZ 0.0 DFX/DY 0.0 DFX/DZ 0.0 DFX/DALX 0.0 DFX/DALY 0.0

BEARING NO. 1
 PARTIAL DERIVATIVES (CONTINUED)
 DFX/DX 0.0 DFX/DY 0.0 DFX/DZ 0.0 DFX/DALX 0.0 DFX/DALY 0.0
 DFX/DZ 0.0 DFX/DY 0.0 DFX/DZ 0.0 DFX/DALX 0.0 DFX/DALY 0.0

[illegible]

INDIVIDUAL KULLER DATA

ROW	COL	ITEM	UNIT	QTY	PRICE	TOTAL
1	1	ROLL UP	INCH	1	1.00	1.00
2	1	ROLL UP	INCH	1	1.00	1.00
3	1	ROLL UP	INCH	1	1.00	1.00
4	1	ROLL UP	INCH	1	1.00	1.00
5	1	ROLL UP	INCH	1	1.00	1.00
6	1	ROLL UP	INCH	1	1.00	1.00
7	1	ROLL UP	INCH	1	1.00	1.00
8	1	ROLL UP	INCH	1	1.00	1.00
9	1	ROLL UP	INCH	1	1.00	1.00
10	1	ROLL UP	INCH	1	1.00	1.00
11	1	ROLL UP	INCH	1	1.00	1.00
12	1	ROLL UP	INCH	1	1.00	1.00
13	1	ROLL UP	INCH	1	1.00	1.00
14	1	ROLL UP	INCH	1	1.00	1.00
15	1	ROLL UP	INCH	1	1.00	1.00
16	1	ROLL UP	INCH	1	1.00	1.00
17	1	ROLL UP	INCH	1	1.00	1.00
18	1	ROLL UP	INCH	1	1.00	1.00
19	1	ROLL UP	INCH	1	1.00	1.00
20	1	ROLL UP	INCH	1	1.00	1.00
21	1	ROLL UP	INCH	1	1.00	1.00
22	1	ROLL UP	INCH	1	1.00	1.00
23	1	ROLL UP	INCH	1	1.00	1.00
24	1	ROLL UP	INCH	1	1.00	1.00
25	1	ROLL UP	INCH	1	1.00	1.00
26	1	ROLL UP	INCH	1	1.00	1.00
27	1	ROLL UP	INCH	1	1.00	1.00
28	1	ROLL UP	INCH	1	1.00	1.00
29	1	ROLL UP	INCH	1	1.00	1.00
30	1	ROLL UP	INCH	1	1.00	1.00
31	1	ROLL UP	INCH	1	1.00	1.00
32	1	ROLL UP	INCH	1	1.00	1.00
33	1	ROLL UP	INCH	1	1.00	1.00
34	1	ROLL UP	INCH	1	1.00	1.00
35	1	ROLL UP	INCH	1	1.00	1.00
36	1	ROLL UP	INCH	1	1.00	1.00
37	1	ROLL UP	INCH	1	1.00	1.00
38	1	ROLL UP	INCH	1	1.00	1.00
39	1	ROLL UP	INCH	1	1.00	1.00
40	1	ROLL UP	INCH	1	1.00	1.00
41	1	ROLL UP	INCH	1	1.00	1.00
42	1	ROLL UP	INCH	1	1.00	1.00
43	1	ROLL UP	INCH	1	1.00	1.00
44	1	ROLL UP	INCH	1	1.00	1.00
45	1	ROLL UP	INCH	1	1.00	1.00
46	1	ROLL UP	INCH	1	1.00	1.00
47	1	ROLL UP	INCH	1	1.00	1.00
48	1	ROLL UP	INCH	1	1.00	1.00
49	1	ROLL UP	INCH	1	1.00	1.00
50	1	ROLL UP	INCH	1	1.00	1.00
51	1	ROLL UP	INCH	1	1.00	1.00
52	1	ROLL UP	INCH	1	1.00	1.00
53	1	ROLL UP	INCH	1	1.00	1.00
54	1	ROLL UP	INCH	1	1.00	1.00
55	1	ROLL UP	INCH	1	1.00	1.00
56	1	ROLL UP	INCH	1	1.00	1.00
57	1	ROLL UP	INCH	1	1.00	1.00
58	1	ROLL UP	INCH	1	1.00	1.00
59	1	ROLL UP	INCH	1	1.00	1.00
60	1	ROLL UP	INCH	1	1.00	1.00
61	1	ROLL UP	INCH	1	1.00	1.00
62	1	ROLL UP	INCH	1	1.00	1.00

[illegible]

ROLLING ELEMENT BEARING ANALYSIS PROGRAM (5 DEGREES OF FREEDOM)

MULLER BEARING ANALYSIS - H108KD7 - RESEARCH

INPUT DATA FOR INDIVIDUAL BEARINGS

BEARING NO.	TYPE OF BEARING	NUMBER OF ELEMENTS	ELEMENT DIAMETER	PITCH DIAMETER	CONTACT ANGLE	RACE CURVATURES	DIAMETRAL CLEARANCE	BEARING LOCATION
1	CYL	18	2.1250E-01	2.1250E-00	0.0	OUTER 0.0	1.5000E-03	0.0
1	ROLL LENGTH (EFFECTIVE)	2.4080E-01	MODULUS OF ELASTICITY	2.9000E-07	POISSONS RATIO	FATIGUE CONSTANT	VALUES OF LAMBDA	
1							OUTER 4.9500E-04	INNER 6.6000E-01
1	ALONG X	INITIAL DISPLACEMENTS AT HEARING CENTER	ALONG Z	ALONG Y	ABOUT X	ABOUT Y	AXIAL PRELOAD	PRELOAD DEFLECTION
1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1	WET HULL SLOPE	LOAD-LIFE EXPONENT	AXIAL FLOAT	RADIAL FLOAT	EIA (DEG)	CONE RIB DIA. (IN)	SHOULDER CLEARANCE	SHOULDER HEIGHT (IN)
1	1.1250E-00	3.333E-00	NO	NO	0.0	0.0	0.0	0.0
1	CAGE OPENING	AXIAL SPRING	ROLL CYLN. LENGTH	CROWN	HALL EXP.	RELIABILITY	MATERIAL LUBRICATION	
1	0.0	NO	1.7200E-01	3.0270E-01	0.0	1.0000E-00	1.0000E-00	

INPUT DATA FOR BEARING SYSTEM

EXTERNAL FORCES AND MOMENTS APPLIED TO SHAFT

ALONG X	ALONG Y	ALONG Z	ABOUT X	ABOUT Y	ABOUT Z
F1	F2	F3	F4	F5	F6
7.0000E-03	-2.8600E-03	0.0	0.0	0.0	0.0

INNER RACES ROTATE WITH RESPECT TO LOAD
OUTER RACES STATIONARY WITH RESPECT TO LOAD
PROBLEM IS POSED IN FOLLOWING DEGREES OF FREEDOM
ALONG X, Y, Z

[illegible]

INDIVIDUAL ROLLER DATA

ROW
 ROLLER
 LOCATION ANGLE (DEG)
 LAMINA WIDTH (IN)
 EFFECTIVE LENGTH (OUTER) (IN)
 CONE ROLL FORCE (LBS)
 ROLLER HALF ANGLE (DEG)

1
 1.80000E-02
 1.20300E-02
 2.40600E-01
 0.0
 0.0

LAMINA NUMBER	DISTANCE TO ROLL CENTER (IN)	LAMINA OUTER	UNIT (LB/IN)	LOAD INNER	HERTZ OUTER	CONTACT STRESS INNER (MEAN PSI)	CONTACT STRESS OUTER	CONTACT SEMI WIDTH INNER	SUBSURFACE STRESS (PSI)	SHEAR (INNER) DEPTH (IN)
1	-1.1420E-01	2.7480E-03	2.7480E-03	2.7480E-03	2.3120E-05	2.7354E-05	5.9414E-03	5.2137E-03	1.0075E-05	4.0985E-03
2	-1.0225E-01	3.0136E-03	3.0136E-03	3.0136E-03	2.4215E-05	2.7598E-05	6.24630E-03	5.4590E-03	1.0551E-05	4.0920E-03
3	-9.8115E-02	3.3286E-03	3.3286E-03	3.3286E-03	2.5445E-05	2.8668E-05	6.5390E-03	5.6714E-03	1.0888E-05	4.0950E-03
4	-9.6115E-02	3.3286E-03	3.3286E-03	3.3286E-03	2.5445E-05	2.9005E-05	6.5390E-03	5.7381E-03	1.0888E-05	4.0950E-03
5	-9.4210E-02	3.3286E-03	3.3286E-03	3.3286E-03	2.5445E-05	2.9005E-05	6.5390E-03	5.7381E-03	1.0888E-05	4.0950E-03
6	-9.2075E-02	3.3286E-03	3.3286E-03	3.3286E-03	2.5445E-05	2.9005E-05	6.5390E-03	5.7381E-03	1.0888E-05	4.0950E-03
7	-8.9845E-02	3.3286E-03	3.3286E-03	3.3286E-03	2.5445E-05	2.9005E-05	6.5390E-03	5.7381E-03	1.0888E-05	4.0950E-03
8	-8.7615E-02	3.3286E-03	3.3286E-03	3.3286E-03	2.5445E-05	2.9005E-05	6.5390E-03	5.7381E-03	1.0888E-05	4.0950E-03
9	-8.5385E-02	3.3286E-03	3.3286E-03	3.3286E-03	2.5445E-05	2.9005E-05	6.5390E-03	5.7381E-03	1.0888E-05	4.0950E-03
10	-8.3155E-02	3.3286E-03	3.3286E-03	3.3286E-03	2.5445E-05	2.9005E-05	6.5390E-03	5.7381E-03	1.0888E-05	4.0950E-03
11	-8.0925E-02	3.3286E-03	3.3286E-03	3.3286E-03	2.5445E-05	2.9005E-05	6.5390E-03	5.7381E-03	1.0888E-05	4.0950E-03
12	-7.8695E-02	3.3286E-03	3.3286E-03	3.3286E-03	2.5445E-05	2.9005E-05	6.5390E-03	5.7381E-03	1.0888E-05	4.0950E-03
13	-7.6465E-02	3.3286E-03	3.3286E-03	3.3286E-03	2.5445E-05	2.9005E-05	6.5390E-03	5.7381E-03	1.0888E-05	4.0950E-03
14	-7.4235E-02	3.3286E-03	3.3286E-03	3.3286E-03	2.5445E-05	2.9005E-05	6.5390E-03	5.7381E-03	1.0888E-05	4.0950E-03
15	-7.2005E-02	3.3286E-03	3.3286E-03	3.3286E-03	2.5445E-05	2.9005E-05	6.5390E-03	5.7381E-03	1.0888E-05	4.0950E-03
16	-6.9775E-02	3.3286E-03	3.3286E-03	3.3286E-03	2.5445E-05	2.9005E-05	6.5390E-03	5.7381E-03	1.0888E-05	4.0950E-03
17	-6.7545E-02	3.3286E-03	3.3286E-03	3.3286E-03	2.5445E-05	2.9005E-05	6.5390E-03	5.7381E-03	1.0888E-05	4.0950E-03
18	-6.5315E-02	3.3286E-03	3.3286E-03	3.3286E-03	2.5445E-05	2.9005E-05	6.5390E-03	5.7381E-03	1.0888E-05	4.0950E-03
19	-6.3085E-02	3.3286E-03	3.3286E-03	3.3286E-03	2.5445E-05	2.9005E-05	6.5390E-03	5.7381E-03	1.0888E-05	4.0950E-03
20	-6.0855E-02	3.3286E-03	3.3286E-03	3.3286E-03	2.5445E-05	2.9005E-05	6.5390E-03	5.7381E-03	1.0888E-05	4.0950E-03

DATE
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7-8