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## 1.0 SCOPE

The purpose of this report is to summarize the task requirements of the High Speed Bearing and Gyro Wheel Evaluation Program of NASA Contract NAS-8-11356. The results obtained from life testing and gyro performance testing for all of the various bearing assemblies, lubricants, and motors assembled will be presented, as well as conclusions and recommendations.

DEVELOPMENT OF IMPROVED PERFORMANCE

HIGH SPEED SPIN BEARING & GYRO WHEEL

PROGRAM

FINAL REPORT

NAS-8-11356

PREPARED FOR:

National Aeronautics and Space Administration
George C. Marshall Space Center
Huntsville, Alabama

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# DEVELOPMENT OF IMPROVED PERFORMANCE HIGH SPEED SPIN BEARING AND GYRO WHEEL PROGRAM

NAS -8-11356

FINAL REPORT

## 2.0 INTRODUCTION

### 2.1 Phases I, II, III

In response to NASA Procurement Request 1-4-40-01125 pertaining to the evaluation and life testing of gyro spin axis bearings developed by Marlin Rockwell Corporation, a proposal (7521-64-12) was submitted by Bendix describing the life test and evaluation program to be performed for Phases I, II, and III. The major purpose of these phases was to evaluate various bearing surface finishes using the present Marlin-Rockwell "state-of-the-art" finish as a basis for comparison. The first three phases of this program were defined as follows:

Phase I - Evaluation of "state-of-the-art" bearings. (Four bearing assemblies to be life tested)

Phase II -Evaluation of eight lots of twelve bearings per lot, to be tested as in Phase I. (Twenty-four bearing assemblies to be life tested.)

Phase III -Evaluation of thirty-six bearings utilizing manufacturing improvements indicated by results of Phase I and II. (Four bearing assemblies to be life tested.)

Phase I bearings were manufactured utilizing 52100 steel produced from an air-melt process, while the bearings of Phase II and III were manufactured from consumable electrode vacuum melt steel. The bearing and shaft assembly, as produced by the Marlin-Rockwell Company, conformed to NASA's drawing GC 425376. These components were treated as a single lot, by Marlin-Rockwell, up to the final finishing process, where they were randomly divided into eleven equal lots and then processed according to the predetermined finishing process. All balls were from the same heat of steel and same ball-lap load. Likewise all retainers were made from the same lot of phenolic material. In this way, the variables between lots were reduced to those induced by race finishing procedures.

As sufficient bearing assemblies were made available at the start of the program it was decided to inspect sample parts from each surface finish group for contamination, retainer properties, torque, etc. These sample parts would not be used for life testing. In addition all other parts were to be assembled as soon as possible after the sealed containers were opened. There was to be no further cleaning, centrifuging, or other processing, that could affect the surface conditions, lubrication, or other controlled parameters of the bearing assembly. The bearings upon assembly into rotors were torque tested and the motor preload set. The rotor assembly used was of the standard production Saturn AB-5 design utilizing monel for the flywheel and endbells, and P6 hysteresis lamination material. This wheel operates on 26 volts, 3 phase, 400 cycle excitation, at 24,000 rpm, and has an angular momentum of 2 x $10^6$ gms $cm^2$/sec.

Upon completion of the motor preload setting,the wheel assemblies were dynamically balanced and placed on life test. The motors were run until operating failure occurred. Failure being specified by preload, torque, or performance deterioration as generally accepted by NASA in previous bearing study programs, and also being used for the Saturn production effort. During life testing the failure criteria, and other parameters, were to be tested on a monthly basis. These tests were to include:

1. Preload
2. Variation of free lubricant (intermediate speed torque test)
3. Motor performance
    a. power consumption
    b. run-up time
    c. run-down time
4. Dynamic balance
5. High speed torque tests

All assembly and test data was recorded in a log book for each life test bearing. At a point where the bearing was judged to have failed, or to be unsatisfactory for use within an inertial gyro, the motor was disassembled, and the complete motor and bearing assembly carefully inspected, and the visual observations recorded. The bearing assembly was then carefully packaged and returned to Marlin-Rockwell for retesting, reinspection of critical dimensions, and analysis of the nature and cause of failure. A joint meeting was then held with the NASA technical director, MRC and Bendix personnel to discuss the failure.

In total forty-three (43) motors were assembled and tested for all three phases, as compared to the contractual requirement of thirty-one (31). The assemblies were made as follows:

| | | |
|---|---|---|
| Phase | I | 5 assemblies, |
| Phase | II | 30 assemblies, |
| Phase | III | 8 assemblies. |

Two of the Phase III motors were also assembled into inner cylinder and cover assemblies, and tested in Saturn AB-5 gas bearing assemblies for motor performance and mass stability.

## 2.2 Phase IV

In response to NASA request for quotation, (DCN 17-40-01125) Bendix submitted a proposal (7521-66-23) in November of 1966 for Phase IV of this program. In general this task was to investigate and qualify special lubricants to replace Terresso V-78 which was the only qualified gyro spin axis bearing lubricant at that time. In specific the investigation was to include the suitability of KG80 oil, manufactured by Kendall Refining Co., as a replacement. The investigation was also to include:

a. determination of separator characteristics, oil retention, bleed-rate, etc.,
b. determination of dynamic characteristics of

bearing when assembled into a gyro wheel, torques, run-down times etc, and

c. life testing of gyro wheels containing bearings lubricated with replacement oils.

A total of twelve (12) New Departure bearing assemblies, N.D. No. 2930740, were supplied as Government Furnished Property to complete this phase of the program. However, it soon became obvious that something was radically wrong with these bearing assemblies, as evidenced by the high mortality rate during the first one-hundred hours (100) of running. It was at this time that the scope of work for Phase IV was expanded to include the investigation of bearing surface chemistry, as well as the effects of retainer designs and materials on bearing life and performance.

A cleaning procedure was devised that would make the bearing metal parts more wettable, as determined by an elementary but repeatable test. However, there is still much more work to be done in this area before a thorough understanding, and control, of bearing wetability can be effected.

In total twenty one (21) gyro motors were assembled, and tested with either one or more of the variables being investigated. The criteria for failure was the same as that established for Phases I, II and III.

## 2.3 Phase V, VI

In response to NASA Procurement Request DCN-1-7-40-01125-S1, a proposal (7521-66-27) was submitted by Bendix in January of 1967 to include Phases V and VI of this program. This program was to include the assembly of bearings, furnished by NASA, into gyro motors and their evaluation with regards to life and performance.

The bearings supplied under Phase V contained 52100 steel, beryllium, and elkonite shaft materials, different surface finishes on the inner and outer races, as well as different surface finish, combinations within the three above mentioned shaft materials. The balls for this series of bearings were from different melts and manufacturing lots than those balls that were utilized in the first three phases. The retainers were also manufactured from a different batch of phenolic material than those used in the first three phases.

All of the bearing assemblies containing 52100 steel shafts were assembled into motors utilizing monel flywheels and endbells, as previously described for Phases I, II, and III. The bearing assemblies utilizing either beryllium or elkonite shaft material were assembled into motors containing elkonite flywheels, and beryllium endbells. The hysteresis material, wheel excitation, speed and angular momentum were exactly the same as for this motor as they were for the monel wheel assembly. This new motor design is identical to that currently being assembled in production for use on Saturn platforms.

In addition two motors were assembled into inner cylinder and cover assemblies, and tested in Saturn AB-5K8 gas bearing assemblies for motor performance, and mass stability.

A total of forty-one (41) gyro motors were assembled and evaluated as compared to the contract requirement of thirty-six assemblies for this phase. However, an additional six (6) bearing assemblies were supplied by NASA and were utilized for further Phase IV testing and evaluation.

Phase VI required the further evaluation of five bearings, to be supplied by NASA, that incorporated the design improvements recommended from Phase V. However, due to the undetermined length of time required to perform life testing on this phase, as well as on previous phases, and the fact that many motor assemblies from the earlier phases were still running, it was decided by NASA to cancel this phase of the program and enter into the next phase, or Phase VII.

## 2.4 Phase VII

In general Phase VII was established by NASA, to incorporate into one phase all of the remaining motors on life test from the previous phases, as well as the continuing investigations into new lubricants, retainer designs, etc., as defined under Phase IV. Bendix's proposal (7121-68-3) was submitted in August of 1968 in response to NASA proposal request DCN 1-9-50-01125.

The results and continued testing, as required by Phase VII, will be presented in the following sections under the original task against which the motor assembly was made.

## 3.0 CONCLUSIONS AND RECOMMENDATIONS

### 3.1 Phase I, II, III

The main, and most significant variable, affecting gyro motor life between bearings assembled in Phases I, II, and III is the bearing surface finish. The basic bearing steel, the lubricant, the ball size and lap load, and the retainer material were all from the same lots of material for these three phase. The gyro-rotor design was not varied, neither was the motor assembly personnel nor assembly procedures. Therefore, the life test data gathered is indicative of the relative merit of each surface finish. Based on the number of hours accumulated the surface finishes may be ranked as follows when compared to the "A" and "B" finishes, which are used as a basis:

| | | |
|---|---|---|
| 1. | C | Best |
| 2. | DB | Better |
| 3. | I | Possibly better |
| 4 | D | Possibly equal |
| 5 | E,F,G,H | Inferior |

The base line "A" and "B" finish when combined produce a statistically valid base for comparison. The amount of bearings run, and the hours accumulated on the "C" type finish also comprise a statically valid sample. This is also true to a lesser degree with the "D" and "DB" results.

The life test results of Phases I, II and III show that bearing surface finishes can be generated that will be conducive to extended bearing and gyro motor life.

The surface finishing processes that left a uni-directional and circumferential pattern on the raceways were superior to those which left a cross-race or irregular pattern.

It is apparent that bearings containing certain type surface finishes are more capable of performing satisfactorily for long periods of time even though their geometry, with respect to other type finishes, is not as good. This is evidenced by the fact that the bearings containing the "C" type finish were the poorest with respect to geometry, as measured and recorded by the Proficorder, but were far superior in terms of life. On the other hand the "D" type finish, containing the best geometry of all the bearing types tested, was only equal in life test results to the base line "A" and "B" type finishes. However, with the subsequent improvement of the"D" finish, by string-polishing, the resultant "DB" type bearings outperformed both the original "D" and "B" type finishes.

These results pose a paradox. Both the "D" and "C" finishes leave a circumferential pattern which is more rough than "B" finish. The "D" finish with the best geometry did not exhibit the best life of all bearings. Yet the hours accumulated by the rougher finish, poor geometry bearings were unchallenged by any other type until the "B" modified "D", or "DB", finish was tested. Therefore, the two finishing processes exhibiting the best life are those with apparently opposing roughness and geometry characteristics.

The improvement of the original "D" type finish, by means of the "B" finishing string polish, and the relative success of the "I" type finish (basic "B" finish) leads to the conclusion that some string polishing is desirable to improve the race roughness, as generated by conventional techniques.

The non-standard "C" finish is superior to all other finishes from a life standpoint. The failures on the "C" finish were nearly all caused by lack of oil available for lubrication. Examination of those races showed little metal deterioration. The race finish appeared improved through thousands of hours of ball lapping by running.

While the non-standard "C" finish may possibly be improved upon by other operations, any extension in life will also necessarily depend on improved lubrication carrying methods.

## 3.2 Phase IV

### 3.2.1 Surface Chemistry Investigation

Certain processes and solvents can cause bearing metal parts to become non-wettable. Other processes can "seal" contaminants and cause the parts to become virtually impossible to "clean" through conventional means. Most bearing races can be made wettable by the solvent cleaning processes developed in Phase IV. Most bearing balls will be made only marginally "wettable" by these processes.

Bearings made "wettable" are better able to survive the point often referred to as "infant mortality". That is, bearings made "wettable" have a much lower incidence of failure in less than 100 hours. This fact was further borne out by results in the build program after the solvent cleaning processes developed and tested on Phase IV were adapted.

The ion bombardment process initiated in Phase IV is very effective in cleaning bearing metal parts. All balls and races cleaned by this process become 100% wettable. This process should be further investigated.

From the results of the wettability tests, and life test comparisons between wettable and non-wettable bearings, it can be concluded that bearings can be made more wettable, and that there is correlation between wettability and bearing life. Although advances have been made, there are still problems which exist and vast areas open for further investigation. Races originally considered wettable can still develop dry spots after short periods of running. While this is not due to the gross "poisoning" conditions resolved in Phase IV, investigation into this phenomenon may produce great dividends in increased bearing life and understanding of the bearing surface chemistry phenonena.

### 3.2.2 Lubricant Investigation

Due to the problems with the ND bearing assemblies initially intended for use with this phase, the number of bearings run specifically for life test of a Teresso V-78 lubricant replacement became limited. Replacement oils were then necessarily run in conjunction with other variables being tested during this phase. Based on Phase IV life test results, and the successful life and gas bearing tests performed on a production unit containing KG80 oil during a constantly monitored 5,000 hour period, it can be stated that KG-80 is a suitable replacement for Teresso V-78.

Therefore KG-80 oil was gradually introduced into the production assembly program. Constant monitoring has shown that the gyro motor build yields, and the final gas bearing performance are better with the KG-80 lubricated bearings.

3.2.3 Retainer Investigation

The phenolic retainer design used on the MRC bearings, as well as the other type bearings tested in this phase of the program, will occasionally yield a "lot" of retainers that are dynamically unstable. The cause of this instability is currently unknown, as both the retainers and the bearings into which they are assembled conform to specification requirements. It is therefore desirable to optimize, or obtain a modification to the current design that would always produce a dynamically stable retainer.

The scalloped, under-cut type retainer design, developed as part of Phase IV, yields the most dynamically stable retainers of all the designs tested. This type retainer design has performed satisfactorily even on retainers known to be dynamically unstable prior to being modified per this design. This is true for both the phenolic, and the bi-material or composite, type retainers tested.

As a result of the successful number of life test hours obtained on each motor assembly containing phenolic scalloped retainers, this design has been introduced into the production assembly effort. The combination of scalloped phenolic retainers, and KG-80 oil, has produced a higher gyro motor assembly yield, as well as an improvement in overall gas bearing mass stability.

The composite retainer can be fabricated, impregnated and made dynamically stable. The oil retention characteristics are superior to that of phenolic, with the bleed rate characteristics being comparable. However, since only two bearing assemblies utilizing this design were life tested the total affect on motor performance and life cannot be fully determined.

## 3.3 Phase V

While the average bearing geometry anomalies generated by machining are small, in the low microinch range, and in some cases do not affect bearing life, the energy levels generated at certain frequencies can cause detrimental effects in the final gyro motor application. Other geometric anamolies produced by damage or misalignment are almost always detrimental to both bearing life and final unit performance.

The frequencies generated by these situations and the energy levels produced can be detected with the proper instrumentation. Those situations caused by misalignments, defects, or damage can be separated from those generated by machining. The identification and

and monitoring of these various frequencies can serve as a valuable tool for the evaluation and trend analysis of motor performance both at the motor level and at higher assemblies.

The surface finish combinations used to determine the affects of surface finish on lubrication life, and performance were selected from the best finishes determined from the results of Phases I, II, and III.

Of the forty-one motors assembled and tested only two were premature failures with all others having run approximately 2,000 hours and better. Two wheels are running in excess of 10,000 hours with the average life of other wheels being in excess of 5,000 hours.

However, the sample sizes are small for each surface finish and bearing shaft material combination, therefore a statistically significant conclusion can not be reached. Since 52100 steel was used in Phases I, II, and III, a general comparison of all life test hours in this phase will be made based on the surface finish and 52100 steel shaft combination.

The following chart compares similar surface finishes verses bearing shaft materials for the average life test hours accumulated:

| Shaft Material | | 52100 | | Bery. | | Elk. |
|---|---|---|---|---|---|---|
| Surface Finish | Sample Size | Avg. Test Hours | $S_S$ | Avg. Test Hours | $S_S$ | Avg. Test Hours |
| CCM | 4 | 5402+ | 4 | 4710 | | |
| IDB | 3 | 6615+ | | | 3 | 7222+ |
| IC | 3 | 6061+ | | | 3 | 3112 |
| DBC | 3 | 4606+ | 4 | 6910 | | |
| CDB | 3 | 5021 | 4 | 5979 | | |
| CI | 3 | 5745 | 4 | 6579+ | | |

+ indicates a motor still on tests

Gas bearing performance tests have shown that motors containing bearings with "CCM and"DB" surface finishes to be stable. Based on these tests, and the life test data accumulated, bearings have been ordered for the production assembly program utilizing these finishes.

If additional surface finish investigations are to be performed in the future it is recommended that the beryllium shaft, elkonite rotor combination be utilized with either the "CCM" finish,"DB" finish combinations, or the CI type finish.

4.0 DISCUSSION AND RESULTS

4.1 Phase I

Phase I bearings were of the Lot A or "A" type finish. These bearings were machined from 52100 steel produced from an air-melt process. They were manufactured to standard Marlin-Rockwell Corporation processes, were ground, and then string polished to final finish and geometry using #700 grit abrasive.

The bearings were assembled into gyro motors as received from Marlin-Rockwell. Although future modifications of the contract allowed centrifuging excess oil from the bearing retainers, these bearings were assembled un-centrifuged as per contract requirements. Monel type gyro motors were used in this phase as referred to in Section 2.1 of this report. The assembly and test of these bearings followed the standard procedures in Saturn documentation Drawing 1853059 GAS and further described in Section 2.1 of this report.

A total of five bearings from this group were assembled and run on life test. (Refer to Appendix Page 45 for life test data ). Of those units run one bearing assembly, A6, failed prematurely after only 22 hours of running time. The remaining four bearing assemblies averaged 3700 running hours. One of these last four bearings (A1) had run successfully for a total of 4063 hours, and was then disassembled for bearing evaluation purposes, at NASA's request. The bearing was found to still be in excellent condition. However, an excessive amount of oil was evident in and around the raceway area. It should also be noted that this motor gave indication of loss in preload. It could very well be that the loss of preload accompanied by the abundance of lubricant in the raceways accounted for the excellent condition of the bearing after running.

The remaining three bearings A5, A9, and A11 as well as A6 were all found to contain evidence of lubricant and metal degradation on either one bearing side, or on both sides to varying degrees. In all cases the failure could be visually determined by the amount of "sludge" and debris build-up on the races as well as in the separator ball pockets.

4.2 Phase II

Phase II bearings were machined from 52100 steel produced from a consumable electrode vacuum melt (CEVM) process. The differences in final machining operations necessary to produce the final surface finish and geometry are outlined below for the eight different surface finishes produced:

1. Lot B or "B" type finish

   The "B" finish is the same as the control lot "A" finish. The differences between the two are in the method of steel manufacture (CEVM vs air melt), and the grinding technique used in the "B" finish which produced better race geometry through the use of an improved center hole grinder.

2. Lot C or "C" type finish

This finish was generated using a honing stone containing a mixture of 900-1200 grit. The action of the stone was across the race (perpendicular to the direction of ball rotation). However, the speed of the rotating race and cyclic action of the stone across the race is such that the resultant finish is rough and appears circumferential in preference. (Parallel to the direction of ball rotation). (Refer to photo in Appendix).

Apparently unique to the "C" type bearing is the six point lobing characteristic of the outer races noted on the proficorder charts. This was later traced to the method of chucking the outer race during the grinding operation.

3. Lot D or "D" type finish

The "D" finish was generated utilizing a honing stone containing a mixture of 900-1200 grit. The action of the stone was around the race (parallel to the direction of ball rotation). The resultant finish is rough and appears circumferential in preference. The race geometry is better than the "C" type bearing surface finish.

4. Lot E or "E" type finish

The"E" finish was generated in the same manner as the "D" finish except that a stone with 1500 grit abrasive was used.

5. Lot F or "F" type finish

This finish was generated by a honing stone containing a mixture of 900-1200 grit. The direction of honing was at an angle to the direction of the race such that a cross hatched pattern was generated. This pattern had an included angle of $60^{\circ}$ with center lines parallel to the direction of ball rotation.

6. Lot G or "G" type finish

The "G" finish was attained by tumbling the races in a fine abrasive, Carbo-Brite No. 6 chip. The unground areas adjacent to the raceway areas were masked off during this tumbling operation. The purpose of the tumbling was to remove the grind marks from the race surface and to produce a more or less "face less" surface.

7. Lot H or "H" type finish

The original surface finish was generated by a string polishing operation similar to that of the "B" type finish utilizing 700 grit abrasive. Following this operation the races were shot peened with fine glass beads of .0021-.0029 inches in diameter at an Almen intensity of 008N2. The shot peening was performed by the Metal Improvement Company, of Hackensack, New Jersey. The resultant surface finish produced a "speckled" affect which was very rough visually, and also noisey when run on MRC's anderometer test.

8. Lot I or "I" type finish

The races were originally finished using 700 grit abrasive string lap similar to the "B" type finish. The races were then Harperized by tumbling in a Titan 28 abrasive under a 22 "G" load.

All of these bearings were assembled into monel type motors, and tested using the same methods as in Phase I except that excess oil was centrifuged from the bearing retainers prior to assembly. The original requirement was that three (3) bearings of each type finish were to be life tested. However, a total of 7 additional bearings were assembled and tested from groups B, C, and D, as agreed to by both NASA and Bendix personnel.

The 12 bearings assembled with E, F, G, and H type finishes all failed after very short periods of time, with only two bearings G5 and E2 approaching 1000 hours of operating life. Of the remaining ten bearings, six ran less than 100 hours, while the rest had an average life of less than 450 hours. The failures in all of these cases were accompanied by both severe metal and lubricant degradation. The causes of failure were attributed to the type of raceway finish, thereby eliminating these finishes from further consideration for future tasks.

Bearings of the B type finish achieved moderately successful lives. Although three failed in less than 800 hours, one achieved 2800 hours life and the other 12,600 hours. The failures were not directly attributed to the type of race finish by either MRC or Bendix personnel who visually examined each bearing after failure occurred. Two of the early failures and the one that failed after 2800 hours failed due to lack of lubricant. In each of these cases there was sufficient retainer flaking to cause a great deal of sludge to be accummulated in the retainer ball pockets and on the raceway. The remaining early failure was caused by retainer instability as evidenced by an audible noise at synchronous speed, and accompanied by high high power consumption. Therefore, due to the cause of failure being attributed to a source other than the surface finish, and the relative success of the two longer running bearings, it was deemed appropriate that this particular surface finish should be considered for future phases of this program.

The "D" type surface finish also achieved moderate success. Four of the six bearings assembled ran for 1500 to 3500 hours life. The remaining two failed at 400 and 0 hours.

At the point where life test data gave indications of moderate success, and proficorder traces showed that the geometry of the "D" finish to be among the best generated, it was decided to modify the rough finish of the "D" surface by a string polish operation similar to that of the "B" finish. In Phase III, which succeeded Phase II, several such modified bearings were tested, and identified as a "DB" type surface finish.

Except for the "C" type surface finish, the two bearing assemblies containing the "I" type finish were more successful than any of the previously mentioned lots. One motor ran for approximately 3,800 hours, while the other operated satisfactorily for 11,642 hours. However, due to the late delivery of these bearings, and subsequent assembly into motors, this particular surface finish was not considered in Phase III of this program. Further, testing with bearings containing the "I" type finish was subsequently performed as part of Phase V, which will be discussed in Section 4.5.

The most successful finish tested in Phase II was the "C" type finish. Bearing C11 exhibited high noise levels and was not life tested. Bearings C5, C6 and C7 ran 15,268 hours, 22,161 hours and 16,982 hours respectively. Bearing C9 was disassembled after 13,284 hours of successful operation for a visual examination. The bearing components were found in good condition, and after evaluation the bearing was reassembled with no additional cleaning or lubricant being added. This bearing failed some 2500 hours later for a total life of 15,801 hours.

Although the "C" type finish is very rough and the outer race geometry the worst of those tested, these bearings achieved the longest and statistically most consistant lives. After 15, - 20,000 hours the surface finishes appear better than when assembled, and the limiting factor in bearing life appears to be the amount of oil available in the bearing retainer.

## 4.3 Phase III

Based on the results of Phases I and II it was decided that the "B", "D", and "C" type finishes all warranted further investigation in Phase III. It was further agreed that the "D" finish was to be modified by the polishing procedure of the "B" type finish, thereby producing the "DB" surface finish. The polishing operation served to reduce the roughness of the circumferential hone lines of the "D" finish, while maintaining the geometry associated with the "D" type finish.

Four bearings of each surface finish, "C" and "DB", were assembled and tested in this phase, following the same procedures and criteria as used in Phases I and II. It should be noted that there was an elapsed period of approximately 18 months from the time the "C" type bearings of Phase II were fabricated, to those of Phase III. The balls and retainers for these bearings were from the same groups as those utilized in Phases I and II.

Of the four "DB" type bearings assembled one failed after 5,400 hours, another after 19,000 hours, with one still running satisfactorily after 24,000 hours. The remaining bearing and motor was assembled into an inner cylinder assembly after attaining 1500 hours of successful life testing. The inner cylinder was then placed into a Saturn AB-5K8 gas bearing assembly and tested for performance and mass stability where it functioned satisfactorily.

Three of the bearings with the "C" type surface finish ran for 4,800 hours, 17,200 hours and 17,600 hours before failure occurred. The remaining bearing is still running, after 11,000 hours, in a Saturn gas bearing inner cylinder. The exceptional performance of this motor in the gas bearing assembly, and the success of the remaining units on life test lead to the qualification of MRC as a bearing source on the Saturn production program for the "C" type surface finish. Also based on these results the "DB" and "C" finishes were applied to bearing assemblies in subsequent phases of this program.

## 4.4 Phase IV

### 4.4.1 Wettability

Twelve New Departure bearings were supplied by NASA for this phase of the program, the purpose of which was to evaluate various lubricants for possible replacement of Terresso V78, the only lubricant qualified for use in the Saturn production gyroscope motors. The first five bearings, containing the test lubricants, were assembled into motors and placed on test. The results were catastrophic in that only one assembly ran for a period of 100 hours. Disassembly and analysis of the bearings indicated very heavy wear tracks on all races, some lubricant degradation, but in general sufficient lubricant remained in and on the retainer to satisfactorily operate in excess of the number of hours actually run on test.

A sixth bearing was assembled into a motor using Teresso V78 as the bearing lubricant, for control purposes in an attempt to determine if the test lubricants, or the basic metal hardware was the cause of the previous motor failures. The motor was run for a total of 37 hours when failure occurred. Disassembly and analysis of this unit revealed the same conditions to exist as was noted previously for the 5 motors containing the test lubricants. Further evaluation of the 6 failed bearing assemblies revealed the effects of what appeared to be lubricant starvation of the raceway areas. This affect would normally be accepted if the motors had run for longer periods of time. The fact that "free" lubricant appeared on all races, balls and the retainer indicated some other phenomena was the true cause of the failure mode.

At this same time there was a great deal of experimental work being performed at both the Naval Research Lab., and MIT Instrumentation Lab. on "poisoned", or chemically contaminated bearing races, and the affect on bearing wettability and gyro motor life. The scope of this phase was extended to include the investigation of wettability, not only for this program but also to include the bearing assemblies used in production motors. The problem was approached from four standpoints:

1. the determination of a satisfactory and repeatable method of testing for wettability,
2. the establishment of cleaning procedures to make a non-wettable bearing wettable,
3. the determination of the specific cleaning or manufacturing process causing the metal hardware to become non-wettable,
4. the affect of these new cleaning procedures, assuring more wettable bearings, on the life and performance of the bearing and motor assembly.

Due to the vastness of the problem an agreement was reached with Astrionics Lab of N.A.S.A., M.I.T. Instrumentation Lab., Naval Research Labs., Barden, MRC, Bendix, and other concerned parties that a free exchange of technical information, data and test results would take place. This was done to standardize test procedures and equipment, make correlation of test data more meaningful, and reducing the possibility of redundant unsuccessful testing.

A standard test procedure was established utilizing a .002 to .003 inch diameter platinum wire, V78 as the test lubricant, and standard size drops of the oil, which when applied to a newly cleaned and dry race or ball, would theoretically develop a $10 \times 10^{-6}$ inch film on the entire race.

The extent of migration of the oil on the metal part after an 18 hour period in a controlled environment determines the wettability of the piece. A race is considered acceptable if the lubricant, when viewed under a black light, has covered a minimum of $180^{\circ}$ from top dead center. A ball is considered acceptable if the lubricant covers a minimum of 40% of the total ball area.

Many cleaning procedures, both chemical and mechanical, were investigated in an effort to convert non-wettable metal parts to wettable and useable hardware.

The procedures investigated included both single and combination type solvent cleaning, use of both acid and alkyline solvents, and the use of distillation type processes.

A general cleaning process was finally established which would accomplish cleaning of the metal parts to meet the above criteria. Additional cleaning processes were developed which will make more "wettable" some marginally "wettable" cases. With the results of investigation into the causes for poor wettability, and the elimination of the most evident of these causes, the general cleaning procedure has been sufficient to maintain wettability to the above criteria.

To investigate possible coloring of life test results, samples from lots of balls used in the bearings for this program were tested for wettability. The results, appearing in Program Report Nos. 41 and 42, show that initial wettability of the balls ranged from 0-100% depending on the lot. Eventual chemical cleaning of the marginal or non-wettable balls increased their wettability. Most races tested were 100% wettable except those New Departure bearings tested after failure in the earlier portion of the oil replacement study. Cleaning of unused bearings from this lot also increased their wettability and life tests of bearings used (ND 27, ND 30) after cleaning were much more successful.

A direct comparison cannot be made due to the change in cage design also made in these bearings. However, a significant increase in running time was realized on the remaining New Departure bearings supplied by NASA.

The balls for bearings used in Phases I, II, and III came from the same lot, and samples from this lot tested to be 100% wettable. Bearings in Phases IV and V contained balls from various lots. None of the balls used in Phases V were from the original lot and are at best only marginally "wettable". Those balls in Phase IV which were not cleaned and still enjoyed acceptable life tests were in C-1 and C-4 and are from the original lot.

Much additional testing was performed in an attempt to determine the original cleaning or manufacturing process causing the wettability problem. The bearing companies were extremely helpful in this aspect of the problem, with many cleaning processes, storage and handling procedures being revised to provide a more wettable bearing assembly. However, there is still much work to be done in this area as there are still many problems that still exist.

The cleaning procedures investigated were not all chemical or mechanical. Also investigated was a cleaning method utilizing ion bombardment. This procedure was developed from methods previously used in glass cleaning applications, and readily adaptable to other types of materials.

Briefly this process utilizes a gas, argon, which is constantly bled into a system at low pressure. The system is constantly evacuated to maintain this pressure and to remove contaminants released by the ion bombardment. The gas is "glow discharged" with the parts being cleaned set between the discharge poles. Ions accelerated in this field strike the parts and cleaning is affected.

The test balls, and bearings cleaned by ion bombardment were cleaned by the apparatus manufacturer, Edwards High Vacuum Inc. Therefore, a limited quantity of ball samples were cleaned and only two entire bearing assemblies were cleaned.

Samples of balls cleaned by ion bombardment were all 100% wettable as were all parts of the two bearings thus cleaned. Balls chemically cleaned seldom exceed 60% wettability. More remarkable is the fact that these ball samples were all non-wettable or "marginal" after previous chemical cleaning. Those balls TCP soaked and non-wettable, a condition never before made wettable, became 100% wettable by this process.

The two "glow discharge" cleaned bearings were life tested. One is on run after 1800 hours. The other failed at 1100 hours. This failure, however, was attributed to the type of retainer design incorporated. The metal parts showed little or no degradation or lube starvation.

Of the bearings chemically cleaned, ND27, C-1, and IC4 have failed. The other six are still on life test with from 1800 to 7500 hours accummulated. The three failures were due to the retainers used. Two failures showed a retainer defect at one ball pocket, while IC-5 was due to the retainer design used.

### 4.4.2 Lubricant Investigation

The task to evaluate oils as a replacement for Teresso V78 was made more difficult by problems encountered with the New Departure bearings supplied for test. Use of these bearings was subsequently discontinued and the results of those bearings run deemed inconclusive. New Departure bearings, from different lots, using separators of different design, and with surfaces prepared thru improved techniques were subsequently used in this phase. Additional bearings were built and lubricated with KG-80. These were extra Phase III bearings with DB or C type finishes. The other lubricants tested were PL 44589 and X13163.

A letter comparing the properties of the oils tested appears in the Appendix of this report. Since KG80 produced by Kendall Refining Company had been strongly recommended, most of the tests conducted were with this oil.

The unfortunate disqualification of results using one lot of ND/H bearings leaves only a small sample of bearings on which to compare the oils. Bearings DB5, C1, C33, C4, and DB13 can be compared with the bearings lubricated with V-78 in Phases II and III. Since the samples are small, no statistically significant conclusion can be reached from these life tests.

Life test data was compiled on a bearing lubricated with KG-80 in the production effort of the Saturn program. This bearing was eventually put on test in a Stabilizing Gyroscope and accumulated 5000 hours of life and test data prior to disassembly. Results of this testing and subsequent bearing analyses has been reported to Astrionics. Based on these results, continuing life test data as part of Phase IV, and the growing use of KG-80 as a gyro bearing lubricating oil, KG80 was phased into the production effort and has virtually replaced Teresso V78 oil.

However, there are now available other lubricants containing many desirable characteristics that have not been tested in the program.

### 4.4.3 Retainer Investigation

The design of bearing retainers to improve both dynamic stability, oil retention and bleed out characteristics were incorporated into Phase IV. As part of this study a composite retainer was designed. This design incorporating a nylasint ring which is encapsulated in a mixture of oil and epoxy was the culmination of research and experimentation initiated prior to the inception of this contract. Many different materials were tested for retention and bleed out characteristics, machinability, ease of handling, repeatibility of physical and chemical characteristics, etc.

The bimaterial retainer design was affected to take advantage of the retention and bleed out characteristics of nylasint yet eliminating instability and machining difficulties encountered with this material. Since the epoxy used exhibited very poor lubricity, and could not be impregnated after cure, a 5% by weight of the lubricant was added prior to cure. The nylasint was impregnated prior to encapsulation. The nylasint ring mean diameter was made the same as the bearing pitch circle. Therefore the bearing ball wipes only the oil from the nylasint and does not contact the epoxy.

Life testing on a limited number of such retainers indicated good life results, (7,000 hours life) yet torque values were higher than with phenolic cages and some cage instability was encountered. As part of Phase IV further development of this retainer was carried out. Sets of retainers were fabricated and an equal number contained each of four lubricants. These lubricants were Teresso V-78 and KG80, PL44589 and X13163 the substitutes under evaluation.

Again problems of dynamic instability and higher torques were encountered. These problems compounded the delivery difficulties by the retainer manufacturer and only two composite cages were life tested in Phase IV. However the torque and stability problems were resolved. The former problem was resolved by increasing the pocket clearance. This did not make the cages more stable however. This problem was successfully resolved by a scalloping technique described later in this section.

Two bearings containing composite retainers scalloped and impregnated with V-78 were life tested. One, NiD.27, ran 1847 hours prior to failure while the other, CDB 11, is still in life test at 1800 hours.

As part of Phase IV an attempt was made to design a universal retainer. This retainer would be adapted for use or replacement in the bearings of the various bearing suppliers for the Saturn production effort. This would be an attempt to eliminate the problem of cage instability encountered on a portion of the phenolic material retainer designs in use.

There are many factors which influence cage stability. Since the bearing size and the viscosities of the oils used and considered for use are similar, and the application, speed and temperature are fixed due to other considerations, the only parameter left for design improvement was within the configuration of the retainer itself.

The retainer design criteria for this application should be,

1. Control of the cage at the outer ring land.
2. Ball and outer land clearances optimized such that ball forces are minimized.
3. Frictional forces between pocket and balls and OD and outer ring bore minimized.
4. Dynamic stability at speed and during run up and run down.

Point one makes necessary the use of a thru hole pocket or a step deep enough in the pocket to offer no control at the ball. Since the step is desirable from the standpoint of ease of assembly, it may be useful to incorporate into the design. However should the ball contact the step when running, premature lubrication degradation can develop.

Reduction of frictional and dynamic forces are important to reduce bearing torques, and localized heating in the retainer pockets. Reduction of these forces decreases the incidence of lubrication degradation, and debris buildup and subsequent depletion of available oil to the bearings.

To determine the stability of a retainer several techniques may be employed. Where the cage instability is severe, it will be audibly distinguished from the bearing noises as intermittant or periodic sounds. More subtle instabilities can be distinguished at run up and run down using a high speed precision torque monitoring system. At speed instabilities can be noted using various equipment. By dwelling at the retainer frequency using frequency-gain measurement devices or torque measuring devices, fluctuating in energy levels or torque levels of the retainer will indicate the degree of retainer instability.

Several designs were attempted and some are still in the process of testing. These included the unbalancing of the cage by various means, changing the angular displacement of cage pockets, changing the pocket stagger, cutting ribs onto the cage O.D., removing the pocket steps, changing the clearances and ratios of ball to pocket and O.D. to outer ring land, among others.

None of these attempts proved successful in all tests although some designs did achieve partial success. Most were unstable during run up of the gyro motor, or after a few moments run at speed. These retainer designs were not further life tested. Retainers with close O.D. and pocket clearness were stable when tested. However both bearing failures with the particular design, B 426 and ID 5 were directly attributed to the tight pocket clearance.

The only completely effective design has been one utilizing a scalloped effect on the cage controlling surface (O.D.). This design is a further development of an earlier ribbed design which was partially successful, and experience with another retainer application. This design incorporates a channel cut in the retainer O.D. for greater oil retention and scallops are cut onto the remaining O.D. sections to reduce the area in contact with the outer ring I.D. Pads on the retainer O.D. are also formed as a result of the scalloping. At speed a hydrodynamic film of oil is developed between the pad on the outer ring I.D. which can further dampen any remaining retainer instability.

This design has been successful in each test with various bearings to effect clearance differences. Subsequently three retainer sets were assembled into bearings for life test. NDN 105, NDSE 162 and ND 30 are running with 7313, 7573, and 3136 hours, thus far.

Other retainer configurations have also been modified by the scalloping technique and made stable. Among these are the composite retainers described earlier, certain thru. hole pocket with tight clearance designs, and standard production run retainers. Limited life tests are being carried out on these designs to determine which materials or clearance combinations will yield greatest life.

Based on these stability tests and life data attained in Phase IV, replacement of unstable retainers has been affected on the Saturn production program. The design evaluated in Phase IV has been used in these bearings and the unstable retainers removed have been modified, and in some cases reused as replacements for other unstable retainers.

## 4.5 Phase V

The purpose of Phase V was to continue the life tests begun in Phases II, III, and IV and to put particular emphasis into effect along the following lines:

1. Effects of ball bearing geometry.
2. Effects of surface finish in lubrication and performance.
3. Study of demensional stability of the gyro motor along the spin axis during operation.
4. Effects of separator design changes.

The effects of ball bearing geometry were investigated as part of Phase V. All motors run as part of Phase V as well as some still running from previous phases were tested to determine the self-generated frequencies and the energy levels at these frequencies. The method of test is described in ETI 3.0 included as the Appendix of this report. A mathematical model was then constructed to determine not only what frequencies might be expected, but also to aid in identifying the frequencies generated.

Several bearings were then disassembled and indiron traces made of the outer race parameters. Some of these were bearings still on life test, some had been recent failures, while the remainder were bearings for life test. An example of an indiron trace and the math model appears in the Appendix to this report.

In order to determine the effect of surface finish on lubrication and performance and to investigate the dimensional stability of gyro motor assembly along the spin axes the following program was followed:

a. Bearing races were mixed to determine whether different finishes on either race might effect life and performance.

b. Different inner race shaft materials were used and matched with different wheel materials.

c. Selected motors of the above mixes as well as others from previous phases and from MRC "C" type finish for the Saturn production effort were tested as Stabilizing Gyroscopes. In this manner dimensional stability could be monitored by changes in the Gyro Musra term.

The effects of separator design changes and lubrication studies were further developed in Phase V. These programs were initiated in Phase IV. However the further development of separator designs, lubrication studies, and surface chemistry investigations were carried out in Phase V. The discussion and data for these programs are described in the Phase IV portion of this report.

The frequency gain plots of each bearing were taken using a 50 cycle tracking filter. Therefore a more continuous type spectrum is presented in these plots. However, the frequencies generating the greatest energy levels are manually scanned and dwelled upon. In this manner a general overall trace is rapidly acquired and the individual frequencies can be readily determined.

The plots taken and the frequencies observed agree with the predetermined math model and with the indiron traces. The small differences in the observed and predetermined frequencies are due to the width of the filter and the deviation in individual bearings from the nominal parameters on which the math model was based.

There was no correlation between race roundness and bearing life borne out in Phase V. However the origin of certain frequencies generated could be determined and this has led to improvements in machining techniques to eliminate objectionable energy levels produced at these frequencies. The recognition of misalignments in gyro motor assemblies, and the identification of some forms of bearing damage or defects were also possible using these frequency gain plots.

The appendix contains a sample frequency gain plot upon which most major frequency levels have been identified.

Although the sample sizes were small, certain race finish and material combinations did appear more desirable than others. Certain bearings are still running on life test, or in cylinders, or units as stabilizing gyroscope motors. None of these bearing combinations including a "C" finish with improved geometry (CCM) were or will be as successful from a life standpoint as the original DB & C type finishes produced for Phases II and III.

The Phase II and III bearings with D B & C finshes had 52100 steel shafts and were assembled into monel wheels. In Phase V this combination was not superior, and possibly inferior to the berylium shaft and elkonite wheel or elkonite shaft elkonite wheel combinations as far as bearing life is concerned. The difference on life between the CCM bearings in Phase V and the C bearing in Phases II and III and in the results of the other Phase V bearings point out the difficulty in reproducing machining techniques where small lots are involved.

Data has been collected on gyroscopes using the various material combinations above. Data from units containing Elkonite bearing shaft and Elkonite wheels have been presented to Astrionics. Unit P35 contains a Phase III "C" finish steel shaft - monel wheel combination. Units P117 and P123 contain berylium shaft elkonite wheel combination, as does P36. The former units contain CCM finish bearings while the latter contain CI finish combinations.

Data thus far shows the CCM finish beryllium shaft-elkonite wheel to be superior. The tests on the CI finish of the same shaft-weel combination is, however, incomplete.

# SECTION 5.0

# APPENDIX

# SECTION 5.1

# LIFE TEST RESULTS

## PHASE I LIFE TEST RESULTS

## CONTRACT NAS 8-11356

Current Status:

| Motor S/N | Brg. S/N | Total Hours Run | Remarks |
|---|---|---|---|
| S12 | A1 | 4,063 | Disassembled 10/12/64 as |
| | | | directed by NASA for bearing |
| | | | evaluation. Motor was running |
| | | | satisfactorily at the time |
| | | | of disassembly. |
| S34 | A5 | 3,174 | FAILED - Disassembled 10/12/64 |
| SE35 | A6 | 22 | INFANT FAILURE |
| SE33 | A9 | 4,135 | FAILED - Disassembled 11/19/64 |
| S 1 | A11 | 3,328 | FAILED - Disassembled 10/12/64 |
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PHASE II LIFE TEST RESULTS

CONTRACT NAS 8-11356

Current Status:

| Motor S/N | Brg. S/N | Total Hours Run | Remarks |
|---|---|---|---|
| SW33 | B1 | 780 | FAILED - Disassembled 1/19/66 |
| SE 36 | B2 | 362 | FAILED - Disassembled 1/19/66 |
| SW 36 | B3 | 2,814 | FAILED - Disassembled 2/4/66 |
| SE 35 | B5 | 12,620 | FAILED - Disassembled 2/4/66 |
| SW 19 | B7 | 556 | FAILED - Disassembled 1/19/66 |
| SE 33 | C5 | 15,264 | FAILED - 10/24/67 |
| S 1 | C6 | 22,161 | FAILED - 12/29/67 |
| S 12 | C7 | 16,982 | FAILED - 4/4/67 |
| SE 34 | C9 | 15,801 | FAILED - 5/25/67 |
| SW 33 | C11 | 0 | Audible noise-Disassembled 1/20/66 |
| SW 13 | D2 | 2,273 | FAILED - Disassembled 2/4/65 |
| SW 34 | D3 | 402 | FAILED - Disassembled 1/19/66 |
| SW 19 | D4 | 1,550 | FAILED - Disassembled 11/19/64 |
| SW 20 | D6 | 3,440 | FAILED - Disassembled 5/25/65 |
| SW 35 | D8 | 0 | Sync problem-Brg.held for disposition |
| | | | by NASA |
| SW 33 | D10 | 1,420 | FAILED - Disassembled 11/19/64 |
| SW 34 | E 2 | 937 | FAILED - Disassembled 2/4/65 |
| SW 36 | E 7 | 595 | FAILED - Disassembled 11/19/64 |
| SW 37 | E 8 | 0 | Bearing assembled twice would not |
| | | | sync at 26 v.Bearing reviewed by |
| | | | NASA |

PHASE II LIFE TEST RESULTS

CONTRACT NAS 8-11356

Current Status:

| Motor S/N | Brg. S/N | Total Hours Run | Remarks |
|---|---|---|---|
| SW81 | F1 | 0 | FAILED -Disassembled 2/4/65 |
| SW80 | F2 | 98 | FAILED -Disassembled 2/4/65 |
| SW79 | F9 | 0 | FAILED -Disassembled 2/4/65 |
| SW38 | G1 | 40 | FAILED -Disassembled 5/25/65 |
| SW69 | G2 | 357 | FAILED-Disassembled 5/25/65 |
| SW39 | G5 | 1,038 | FAILED- Disassembled 5/25/65 |
| SW35 | H2 | 400 | FAILED -Disassembled 11/19/64 |
| SW37 | H3 | 107 | FAILED -Disassembled 11/19/64 |
| SW35 | H5 | 455 | FAILED -Disassembled 5/25/65 |
| SW80 | I3 | 11,642 | FAILED -Disassembled 10/21/66 |
| SW79 | I4 | 3,789 | FAILED -Disassembled 1/20/66 |
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PHASE III LIFE TEST RESULTS

CONTRACT NAS 8-11356

Current Status:

| Motor S/N | Brg. S/N | Total Hours Run | Remarks |
|---|---|---|---|
| SW79 | DB 4 | 24,969 | On Run |
| SW37 | C 21 | 11,250 | On Run in Unit P35 Cylinder |
| | | | XE60 Motor Ran 3,002 hrs. prior |
| | | | to Assembly into Cylinder |
| SE37 | DB 8 | 1,525 | Assembled into AB5-K8 Cylinder |
| | | | SN SB 110 |
| | | | |
| | | | |
| SW13 | C 26 | 17,619 | Failed 7/31/68 (52100) |
| SW81 | DB 6 | 18,957 | Failed 9/23/68 (52100) |
| SW35 | C 29 | 4,780 | Failed 2/7/67 (52100) |
| SW38 | DB 7 | 5,405 | Failed 2/7/67 (52100) |
| SW34 | C 22 | 17,235 | Failed 12/4/68 (52100) |
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**PHASE IV LIFE TEST RESULTS**

**CONTRACT NAS 8-11356**

**Current Status:**

| Motor S/N | Brg. S/N | Total Hours Run | Remarks |
|---|---|---|---|
| SW 38 | MRC-DB- | 14,079 | On Run (KG80) |
| | 13 | | |
| M 226 | ND-N105 | 7,313 | On Run (KG 80 oil) Scalloped |
| | | | Retainers - Phenolic |
| M 6 | NDSE162 | 7,573 | Disassembled(KG 80 oil) at |
| | | | 4,053 Scalloped Retainers - |
| | | | Phenolic |
| M205 | ND 30 | 3,195 | On Run (KG 80 Oil) Scalloped |
| | | | Retainers Phenolic |
| SW 13 | CDB-11 | 1,843 | On Run (KG 80 oil) Scalloped |
| | | | High OD w/thru Hole Pockets |
| | | | Retainer-Phenolic |
| SW129 | NDVBG- | 1,975 | On Run Composite Retainers |
| | 103 | | Scalloped (V78 Oil) |
| SEB 10 | B591 | 1,842 | On Run Glow Discharge (KG 80 |
| | | | Oil)(STD Retainers) |
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PHASE IV LIFE TEST RESULTS

CONTRACT NAS 8-11356

Current Status:

| Motor S/N | Brg. S/N | Total Hours Run | Remarks |
|---|---|---|---|
| SEB 24 | ND 14 | 62 | Failed (KG80) |
| SEB 10 | ND 12 | 44 | Failed (KG80) |
| SW 69 | MRC | 1,086 | Failed (KG80) |
| | DB 5 | | |
| M 150 | ND 24 | 18 | Failed (KG80) |
| M 204 | ND 22 | 197 | Failed (KG80) |
| M 203 | ND 46 | 18 | Failed (X13163) |
| SEB 24 | ND 47 | 37 | Failed (V-78) |
| M 204 | ND 36 | 2,102 | Failed (X13163) |
| S 12 | MRC-C-1 | 4,081 | Failed (KG80) |
| SW 39 | MRC-D33 | 5,654 | Failed (KG80) |
| M 204 | ND 27 | 1,847 | Failed (V78 oil) Composite |
| | | | Retainers (Scalloped) |
| SE 36 | MRC-4 | 7,792 | Failed 10/31/68 (PL44589 Oil) |
| M 203 | B 426 | 1,120 | Failed (KG80 oil) Glow Discharge, |
| | | | Tight O.D. and Pocket Glearance. |
| SW 128 | IC-5 | 1,399 | Failed 3/26/69 |
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**PHASE V LIFE TEST RESULTS**

**CONTRACT NAS 8-11356**

**Current Status:**

| Motor S/N | Brg. S/N | Total Hours Run | Remarks |
|---|---|---|---|
| S 1 | CCM 21 | 9,913 | On Run 52100 |
| E 232 | IDB-4 | 9,142 | On Run 52100 |
| SW 131 | IC-4 | 11,439 | On Run 52100 |
| E 2648 | DBC-8 | 4,393 | On Run 52100 |
| | | | |
| | | | |
| SW 36 | IC -2 | 4,344 | FAILED 5/7/68 52100 |
| SW 35A | IC-3 | 2,400 | FAILED 5/13/68 " |
| SE 35A | CCM-10 | 2,238 | FAILED 3/26/68 " |
| SW 39 | CCM-20 | 1,707 | FAILED 5/20/68 " |
| SW 156 | CCM-23 | 7,756 | FAILED 12/27/68 " |
| SW 129 | CDB-8 | 1,901 | FAILED 7/10/68 " |
| SW 91 | CDB-9 | 6,303 | FAILED 9/23/68 " |
| SW 11 | CDB-10 | 6,859 | FAILED 8/20/68 52100 |
| SW 35A | CI-11 | 115 | FAILED 12/11/67 " |
| SW 36 | CI-12 | 7,486 | FAILED 5/20/69 " |
| SW 80 | CI-14 | 9,635 | FAILED 3/3/69 " |
| SW 33A | IDB-1 | 5,562 | FAILED 8/1/68 " |
| SW 20A | IDB-2 | 5,142 | FAILED 7/31/68 " |
| SW 121 | DBC-11 | 5,417 | FAILED 3/3/69 " |
| SW 128 | DBC-76 | 4,009 | FAILED 11/1/68 " |
| | | | |

PHASE V LIFE TEST RESULTS

CONTRACT NAS 8-11356

**Current Status:**

| Motor S/N | Brg. S/N | Total Hours Run | Remarks |
|---|---|---|---|
| M150 | CI-1 | 7,253 | In Cylinder (SQ87) Ready for |
| | | | final assembly |
| XE194 | CI-2 | 6,164 | In Final Build up Unit P36 |
| XE182 | CI-4 | 10,500 | On Run Bery |
| | | | |
| | | | |
| M 167 | CI-3 | 2,397 | Failed - 5/3/68 Bery. |
| M 203 | DBC-1 | 3,368 | Failed - 2/28/68 Bery. |
| XE 199 | DBC-2 | 7,236 | Failed - 11/27/68 " |
| SEB 26 | DBC-3 | 8,235 | Failed - 2/1/69 " |
| XE 198 | DBC-4 | 8,800 | Failed - 3/2/69 " |
| M 203 | CCM-6 | 2,998 | Failed - 7/31/68 " |
| XE 186 | CDB-1 | 8,014 | Failed - 11/26/68 " |
| XE 184 | CDB-2 | 17 | Failed - 1/10/68 " |
| M 174 | CDB-3 | 9,491 | Failed - 3/21/69 " |
| SEB 10 | CDB-4 | 6,395 | Failed - 9/3/68 " |
| M 209 | CCM-2 | 7,143 | Failed - 9/20/68 " |
| M 205 | CCM-7 | 5,356 | Failed - 10/30/68 " |
| M 215 | CCM 15 | 3,344 | Failed - 3/25/68 " |
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PHASE V LIFE TEST RESULTS

CONTRACT NAS 8-11356

Current Status:

| Motor S/N | Brg. S/N | Total Hours Run | Remarks |
|---|---|---|---|
| M 130 | IDB-8 | 7,585 | On Run Elkonite |
| M 215 | IDB-9 | 6,983 | On Run " |
| | | | |
| | | | |
| M 87 | IDB-7 | 7,097 | Failed 5/20/69 Elkonite |
| M 252 | ID= 7 | 4,296 | Failed 11/26/68 " |
| M 207 | IC- 8 | 3,028 | Failed 9/24/68 " |
| M ,69 | IC- 9 | 2,011 | Failed 9/25/68 " |
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13773 NS

# SECTION 5.2

# LUBRICATION INFORMATION

Navigation & Control Division

Interdepartmental

January 16, 1968

Memo: Mr. T. Wheelock

cc: Mr. J. Pierry
Mr. H. Schulien

Subject: Physical Properties and Corrosivesness and Oxidation Stability of Spin Axis Ball Bearing Lubricants

At your request the lubricants listed below were tested to determine physical properties and corrosiveness and oxidation stability.

(1) Kendall KG-80 oil.
(2) Rohm & Haas PL4459 oil.
(3) Bendix-Gyro Oil X13163

The results of these tests are as follows:

Physical Properties

| | KG-80 | PL-4459 | X13163 | Test Method |
|---|---|---|---|---|
| Viscosity, Centistokes | | | | |
| 100°F | 154.46 | 79.28 | 155.00 | ASTM D-445-61 |
| 210°F | 15.18 | 14.07 | 21.20 | ASTM D 445-61 |
| 0°F(EXT.) | 15,000. | 2200. | 6000. | - |
| -40°F(EXT.) | 410,000. | 19,000. | 75,000. | - |
| Viscosity Index | 106 | 146 | 173 | ASTM D-567-53 |
| Specific Gravity 60°F | 0.8764 | 0.9541 | 0.9795 | None |
| Flash Point | 520°F | 450°F | 470°F | ASTM D-92-57 |
| Fire Point | 600°F | 495°F | 515°F | ASTM D-92-57 |
| Pour Point | +10°F | -60°F | -50°F | ASTM D-97-57 |
| Color (Union) | 1 Minus | 6 | 6 | ASTM D-1500-58T |
| Copper Corrosion | Negative | Negative | Negative | ASTM D-130-56 |

Corrosiveness and Oxidation Stability

Federal Test Method Std. 791a
Method 5308.4
Kendall KG-80 Oil

| | | | |
|---|---|---|---|
| Copper | change | $MG/CM^2$ | .0030 Loss |
| Steel | change | $MG/CM^2$ | .0030 Loss |
| Aluminum | change | $MG/CM^2$ | .0038 Loss |
| Cadmium | change | $MG/CM^2$ | .0775 Loss |
| Magnesium | change | $MG/CM^2$ | .0046 Loss |

(continued - Kendall KG-80 Oil)

Copper visible Corrosion - Discoloration, no corrosion.
Steel visible Corrosion - No discoloration or corrosion.
Aluminum visible Corrosion - No discoloration or corrosion.
Cadmium visible Corrosion - Discoloration - no corrosion.
Magnesium visible Corrosion - No discoloration or corrosion.

No evidence of pitting or etching.

Weight loss resulting from Evaporation of Test Oil .039%
Appearance of test oil - No gumming or separation.
Viscosity before test 130°F 71.91 centistokes
Viscosity after test 130°F 72.36 centistokes
Viscosity Increase .625%
Neutralization number change 0.05

## Rohm & Haas PL-4459 Oil

| | | | |
|---|---|---|---|
| Copper | change | $MG/CM^2$ | .0061 Loss |
| Steel | change | $MG/CM^2$ | .0000 |
| Aluminum | change | $MG/CM^2$ | .0030 Increase |
| Cadmium | change | $MG/CM^2$ | .2944 Loss |
| Magnesium | change | $MG/CM^2$ | .0038 Increase |

Copper visible corrosion - Slight discoloration, no corrosion.
Steel visible corrosion - No discoloration, no corrosion.
Aluminum visible corrosion - No discoloration, no corrosion.
Cadmium visible corrosion - Slight discoloration, no corrosion.
Magnesium visible corrosion - No discoloration, no corrosion.

No evidence of pitting or etching.

Weight loss resulting from Evaporation of Test Oil - None
Appearance of test oil - No gumming or separation.
Viscosity before test - 130°F 43.45 centistokes
Viscosity after test - 130°F 45.11 centistokes
Viscosity Increase 3.92%
Neutralization number change 0.37

## Bendix Gyro Oil X 13163

| | | | |
|---|---|---|---|
| Copper | change | $MG/CM^2$ | .0123 Loss |
| Steel | change | $MG/CM^2$ | .0015 Loss |
| Aluminum | change | $MG/CM^2$ | .0007 Increase |
| Cadmium | change | $MG/CM^2$ | .1077 Loss |
| Magnesium | change | $MG/CM^2$ | .0007 Increase |

Copper visible corrosion - Slight discoloration, no corrosion.
Steel visible corrosion - No discoloration, no corrosion.
Aluminum visible corrosion - No discoloration, no corrosion.
Cadmium visible corrosion - Slight discoloration, no corrosion.
Magnesium visible corrosion - No discoloration, no corrosion.

No evidence of pitting or etching.

(continued - Bendix Gyro Oil X13163)

Weight loss resulting from Evaporation of Test Oil .039%
Appearance of test oil - No gumming or separation.
Viscosity before test 130°F 81.75 centistokes
Viscosity after test 130°F 82.96 centistokes
Viscosity Increase 1.48%
Neutralization number change - 0

Metallurgy & Chemistry Dept.

F. Rodriguez

F. Rodriguez

Approved by: 

FR/mr

Eclipse-Pioneer Division

Interdepartmental

October 20, 1964

Memo: Mr. J. Pierry

cc: Messrs: E. Tronco
H. Schulien
W. A. Johnston

Subject: Determine Physical Properties, Particle Contamination and Infrared Analysis of Spin Axis Ball Bearing Lubricants

Reference is made to my memo of July 9, 1964 in which it was stated that test results will be forwarded upon completion of tests conducted on the following spin axis lubricants.

(1) Eclipse-Pioneer Spin Axis Ball Bearing Lubricant X13163 compounded in January 1963.
(2) Eclipse-Pioneer Spin Axis Ball Bearing Lubricant X13163 compounded in August 1964.
(3) Teresso V-78 oil.
(4) New Departure Gyro Oil "G".

The physical properties and particle contamination of these lubricants are as follows:

Physical Properties

| | Test Method A.S.T.M. | Eclipse-Pioneer Lubricant X1316 Compounded January 1963 Not Filtered Physical Properties Determined January 1963 |
|---|---|---|
| Viscosity, Centistokes | | |
| -65°F EXT. | | 600,000. |
| -40°F EXT. | | 75,000. |
| 0°F EXT. | | 6,000. |
| 100°F | D 445-61 | 155. |
| 130°F | D 445-61 | 73.18 |
| 210°F | D 445-61 | 21.20 |
| 500°F EXT. | | 2.45 |
| Viscosity Index | D 567-53 | 173. |
| Pour Point | D 97-57 | -50°F. |
| Flash Point | D 92-57 | 470°F. |
| Fire Point | D 92-57 | 515°F. |
| Color (Union) | D1500-58T | 6. |
| Specific Gravity 60°F | None | 0.9795 |
| Evaporation Loss (22 Hrs. @250°F) | D 972-56 | 0.80% |
| Galvanic Corrosion (10 days, 80°F. 50% Relative Humidity) | Federal Test Method No.791a | Passes No signs of corrosion or Pitting on test specimens |
| Humidity Cabinet (100 Hrs. 100% Relative Humidity.120°F) | D1748-60T | Passes No signs of corrosion |

## Corrosivity Test
## Corrosiveness and Oxidation

| | | | |
|---|---|---|---|
| Copper, | change | $MG/CM^2$ | .1600 |
| Steel, | change | $MG/CM^2$ | .0400 |
| Aluminum, | change | $MG/CM^2$ | .000 |
| Magnesium, | change | $MG/CM^2$ | .0600 |
| Cadmium, | change | $MG/CM^2$ | .4400 |

| | |
|---|---|
| Copper visible corrosion | Discoloration - no corrosion |
| Steel visible corrosion | No corrosion or discoloration |
| Aluminum visible corrosion | No corrosion or discoloration |
| Magnesium visible corrosion | No corrosion or discoloration |
| Cadmium visible corrosion | No corrosion or discoloration |

Weight loss resulting from evaporation of test oil - None

Appearance of test oil after test - Dark and clear.

Viscosity after test 130°F 76.03 centistokes
Viscosity increase after test 3.89%

## Oil Contamination Analysis

Not determined.

---

## Physical Properties

| | Test Method A.S.T.M. | Eclipse-Pioneer Lubricant X13163 Compounded January 1963 Filtered through .45 micron Filte Physical Properties Determined August & September 1964 |
|---|---|---|
| Viscosity, Centistokes | | |
| -65°F EXT. | | 770,000. |
| -40°F EXT. | | 70,000. |
| 0°F EXT. | | 6,800. |
| 100°F | D 445-61 | 158.04 |
| 130°F | D 445-61 | 81.48 |
| 210°F | D 445-61 | 20.51 |
| 500°F EXT. | | 2.41 |
| Viscosity Index | D 567-53 | 172. |
| Pour Point | D 97-57 | -50°F |
| Flash Point | D 92-57 | 485°F. |
| Fire Point | D 92-57 | 539°F. |
| Color (Union) | D1500-58T | 6 |
| Specific Gravity 60°F | None | 0.9540 |
| Evaporation Loss (22 Hrs. @250°F.) | D 972-56 | 0.80% |
| Galvanic Corrosion (10 days, 80°F 50% Relative Humidity) | Federal Test Method No. 791a | No signs of corrosion or pitting on test specimens. |
| Humidity Cabinet (100 Hrs. 100% Relative Humidity 120°F) | D1748-60T | Passes No signs of corrosion or pitting. |

## Corrosivity Test
## Corrosiveness and Oxidation

| | | | |
|---|---|---|---|
| Copper, | change | $MG/CM^2$ | .0073 |
| Steel, | change | $MG/CM^2$ | .0003 |
| Aluminum, | change | $MG/CM^2$ | .0001 |
| Magnesium, | change | $MG/CM^2$ | .0003 |
| Cadmium, | change | $MG/CM^2$ | .0070 |

Copper visible corrosion - Discoloration - no corrosion.
Steel visible corrosion - No corrosion or discoloration.
Aluminum visible corrosion - No corrosion or discoloration.
Magnesium visible corrosion - No corrosion or discoloration
Cadmium visible corrosion - Slight discoloration - no corrosion

Weight loss resulting from evaporation of test oil - None
Appearance of test oil after test - Dark and clear
Viscosity after test 130°F 88.21 centistokes
Viscosity increase after test 8.25%

### Oil Contamination Analysis

No. of particles per 25 ML. $0.16 \times 10^6$
Largest particle 10 microns

---

## Physical Properties

| | Test Method A.S.T.M. | Eclipse-Pioneer Lubricant X13163 Compounded January 1963 Filtered through 15 micron Filter Physical Properties Determined August & September 1964 |
|---|---|---|
| Viscosity, Centistokes | | |
| -65°F EXT. | | 700,000. |
| -40°F EXT. | | 68,000. |
| 0°F EXT. | | 6,400. |
| 100°F | D 445-61 | 154.60 |
| 130°F | D 445-61 | 76.42 |
| 210°F | D 445-61 | 20.51 |
| 500°F EXT. | | 2.42 |
| Viscosity Index | D 567-53 | 172 |
| Pour Point | D 97-57 | -50°F |
| Flash Point | D 92-57 | 485°F |
| Fire Point | D 92-57 | 539°F |
| Color (Union) | D1500-58T | 6 |
| Specific Gravity 60°F | None | 0.9540 |
| Evaporation Loss (22 Hrs. @ 250°F) | D 972-56 | 0.80% |
| Galvanic Corrosion (10 days, 80°F 50% Relative Humidity) | Federal Test Method No. 791a | Passes No signs of corrosion or pitting on test specimens. |
| Humidity Cabinet (100 Hrs. 100% Relative Humidity, 120°F) | D1748-60T | Passes No signs of corrosion or pitting |

## Corrosivity Test
## Corrosiveness and Oxidation

| | | | |
|---|---|---|---|
| Copper, | change | $MG/CM^2$ | .0010 |
| Steel, | change | $MG/CM^2$ | .0002 |
| Aluminum, | change | $MG/CM^2$ | .0002 |
| Magnesium, | change | $MG/CM^2$ | .0002 |
| Cadmium, | change | $MG/CM^2$ | .0070 |

Copper visible corrosion - Discoloration - no corrosion.
Steel visible corrosion - No corrosion or discoloration.
Aluminum visible corrosion - No corrosion or discoloration.
Magnesium visible corrosion - No ocrrosion or discoloration.
Cadmium visible corrosion - Slight discoloration - no corrosion.

Weight loss resulting from evaporation of test oil - None
Appearance of test oil after test - Dark and Clear
Viscosity after test 130°F 79.51 centistokes
Viscosity increase after test 4.04%

## Oil Contamination Analysis

Number of particles per 25ML. $1.01 \times 10^6$
Largest particle 15 microns

---

## Physical Properties

| | Test Method A.S.T.M. | Eclipse-Pioneer Lubricant X13163 Compound August 1964 Filtered through .45 micron Filte Physical Properties Determined August and September 1964 |
|---|---|---|
| Viscosity, Centistokes | | |
| -65°F EXT. | | 610,000. |
| -40°F EXT. | | 76,000. |
| 0°F EXT. | | 6,000. |
| 100°F | D 445-61 | 152.02 |
| 130°F | D 445-61 | 74.77 |
| 210°F | D 445-61 | 21. |
| 500°F EXT. | | 2.45 |
| Viscosity Index | D 567-53 | 172 |
| Pour Point | D 97-57 | -50°F |
| Flash Point | D 92-57 | 480°F |
| Fire Point | D 92-57 | 549°F |
| Color (Union) | D1500-58T | 6 |
| Specific Gravity 60°F | None | 0.9530 |
| Evaporation Loss (22 hrs. @250°F) | D 972-56 | 0.87% |
| Galvanic Corrosion (10 days, 80°F, 50% Relative Humidity) | Federal Test Method No. 791a | Passes No signs of corrosion or pitting on test specimens. |
| Humidity Cabinet (100 hrs. 100% Relative Humidity, 120°F) | D1748-60T | Passes No signs of corrosion or pitting. |

## Corrosivity Test
## Corrosiveness and Oxidation

| | | | |
|---|---|---|---|
| Copper, | change | $MG/CM^2$ | .0007 |
| Steel, | change | $MG/CM^2$ | .0002 |
| Aluminum, | change | $MG/CM^2$ | .0000 |
| Magnesium, | change | $MG/CM^2$ | .0000 |
| Cadmium, | change | $MG/CM^2$ | .0005 |

Copper visible corrosion - Discoloration - no corrosion
Steel visible corrosion - No corrosion or discoloration
Aluminum visible corrosion - No corrosion or discoloration
Magnesium visible corrosion - No corrosion or discoloration
Cadmium visible corrosion - No corrosion or discoloration

Weight loss resulting from evaporation of test oil - None
Appearance of test oil after test - Dark and Clear
Viscosity after test 130°F 76.64 centistokes
Viscosity increase after test 2.50%

### Oil Contamination Analysis

Number of particles per 25 ML. $0.15 \times 10^6$
Largest particle 30 microns

---

## Physical Properties

| | | Test Method A.S.T.M. | Eclipse-Pioneer Lubricant X13163 Compounded August 1964 Filtered through 15 micron filte Physical Properties Determined August and September 1964 |
|---|---|---|---|
| Viscosity, Centistokes | | | |
| -65°F | EXT. | | 650,000. |
| -40°F | EXT. | | 77,000. |
| 0°F | EXT. | | 6,000. |
| 100°F | | D 445-61 | 151.59 |
| 130°F | | D 445-61 | 74.22 |
| 210°F | | D 445-61 | 20.59 |
| 500°F | EXT. | | 2.42 |
| Viscosity Index | | D 567-53 | 172 |
| Pour Point | | D 97-57 | -50°F |
| Flash Point | | D 92-57 | 480°F |
| Fire Point | | D 92-57 | 549°F |
| Color (Union) | | D1500-58T | 6 |
| Specific Gravity 60°F | | None | 0.9530 |
| Evaporation Loss (22Hrs. @250°F) | | D 972-56 | 0.87% |
| Galvanic Corrosion (10 days, 80°F, 50% Relative Humidity) | | Federal Test Method No. 791a | Passes No signs of corrosion or pitting on test specimens |
| Hmmidity Cabinet (100Hrs. 100% Relative Humidity, 120°F) | | D1748-60T | No signs of corrosion or pitting. |

## Corrosivity Test
## Corrosiveness and Oxidation

| | | | |
|---|---|---|---|
| Copper, | change | MG/CM$^2$ | .0000 |
| Steel, | change | MG/CM$^2$ | .0000 |
| Aluminum, | change | MG/CM$^2$ | .0000 |
| Magnesium, | change | MG/CM$^2$ | .0002 |
| Cadmium, | change | MG/CM$^2$ | .0000 |

Copper visible corrosion - Discoloration - no corrosion
Steel visible corrosion - No corrosion or discoloration
Aluminum visible corrosion - No corrosion or discoloration
Magnesium visible corrosion - No corrosion or discoloration
Cadmium visible corrosion - No corrosion or discoloration

Weight loss resulting from evaporation of test oil - None
Appearance of test oil after test - Dark and Clear
Viscosity after test 130°F 76.20 centistokes
Viscosity increase after test 2.66%

### Oil Contamination Analysis

Number of particles per 25 ML. $0.73 \times 10^6$
Largest particle 15 micron

---

## Physical Properties

| | | Test Method A.S.T.M. | Teresso V-78 Oil Filtered through .45 micron Filter Physical Properties Determined Aug. & Sept. 1964 |
|---|---|---|---|
| Viscosity, Centistokes | | | |
| -65°F | EXT. | | 6,800,000. |
| -40°F | EXT. | | 390,000. |
| 0°F | EXt. | | 14,800. |
| 100°F | | D 445-61 | 160.20 |
| 130°F | | D 445-61 | 70.14 |
| 210°F | | D 445-61 | 17.00 |
| 500°F | EXT. | | 1.85 |
| Viscosity Index | | D 567-53 | 116 |
| Pour Point | | D 97-57 | +16°F |
| Flash Point | | D 92-57 | 530°F |
| Fire Point | | D 92-57 | 541°F |
| Color (Union) | | D1500-58T | 6 |
| Specific Gravity 60°F | | None | 0.8860 |
| Evaporation Loss (22 Hrs. @250°F) | | D 972-56 | 0.83% |
| Galvanic Corrosion (10 days, 80°F, 50% Relative Humidity) | | Federal Test Method No. 791a | Failed- Evidence of corrosion and pitting on test specimens. |
| Humidity Cabinet (100 hrs. 100% Relative Humidity 120°F) | | D1748-60T | Failed Test specimens corroded |

## Corrosivity Test

### Corrosiveness and Oxidation

| | | | |
|---|---|---|---|
| Copper, | change, | $MG/CM^2$ | .0014 |
| Steel, | change, | $MG/CM^2$ | .0004 |
| Aluminum, | change, | $MG/CM^2$ | .0003 |
| Magnesium, | change, | $MG/CM^2$ | .0002 |
| Cadmium, | change | $MG/CM^2$ | .0007 |

Copper visible corrosion - Slight discoloration - no corrosion
Steel visible corrosion - No corrosion or discoloration
Aluminum visible corrosion - No corrosion or discoloration
Magnesium visible corrosion - No corrosion or discoloration
Cadmium visible corrosion - Slight discoloration - no corrosion

Weight loss resulting from evaporation of test oil - None
Appearance of test oil after test - Dark and Clear
Viscosity after test 130°F 72.02 centistokes
Viscosity increase after test 2.68%

### Oil Contamination Analysis

Number of particles per 25 ML. $0.08 \times 10^6$

Largest particle 5 microns.

---

### Physical Properties

| | | Test Method A.S.T.M. | Teresso V-78 Oil Filtered through 15 Micron Filter Physical Properties Determined August and September 1964 |
|---|---|---|---|
| Viscosity, Centistokes | | | |
| -65°F | EXT. | | 6,000,000. |
| -40°F | EXT. | | 350,000. |
| 0°F | EXT. | | 14,000. |
| 100°F | | D 445-61 | 162.79 |
| 130°F | | D 445-61 | 70.37 |
| 210°F | | D 445-61 | 17.41 |
| 500°F | EXT. | | 1.90 |
| Viscosity Index | | D 567-53 | 116 |
| Pour Point | | D 97-57 | +16°F |
| Flash Point | | D 92-57 | 530°F |
| Fire Point | | D 92-57 | 541°F |
| Color (Union) | | D1500-58T | 6 |
| Specific Gravity 60°F | | None | 0.8860 |
| Evaporation Loss (22 hrs @ 250°F) | | D 972-56 | 0.83% |
| Galvanic Corrosion (10 days, 80°F, 50% Relative Humidity) | | Federal Test Method No. 791a | Failed Evidence of corrosion and pitting on test specimens. |
| Humidity Cabinet (100 hrs, 100% Relative Humidity, 120°F) | | D1748-60T | Failed Test specimens corroded |

## Corrosivity Test
## Corrosiveness and Oxidation

| | | | |
|---|---|---|---|
| Copper, | change | $MG/CM^2$ | .0012 |
| Steel, | change | $MG/CM^2$ | .0000 |
| Aluminum, | change | $MG/CM^2$ | .0001 |
| Magnesium, | change | $MG/CM^2$ | .0003 |
| Cadmium, | change | $MG/CM^2$ | .0000 |

Copper visible corrosion - Slight discoloration - no corrosion
Steel visible corrosion - No corrosion or discoloration
Aluminum visible corrosion - No corrosion or discoloration
Magnesium visible corrosion - No corrosion or discoloration
Cadmium visible corrosion - Slight discoloration - no corrosion

Weight loss resulting from evaporation of test oil - None
Appearance of test oil after test - Dark and Clear
Viscosity after test 130°F 71.58 centistokes
Viscosity increase after test 1.71%

## Oil Contamination Analysis

Number of particles per 25 ML. $0.42 \times 10^6$

Largest particle 10 microns

---

## Physical Properties

| | | Test Method A.S.T.M. | New Departure Gyro Oil "G" Filtered through .45micron Filter Physical Properties Determined August and September 1964 |
|---|---|---|---|
| Viscosity, Centistokes | | | |
| -65°F | EXT. | | 15,000,000. |
| -40°F | EXT. | | 700,000. |
| 0°F | EXT. | | 20,000. |
| 100°F | | D 445-61 | 175.27 |
| 130°F | | D 445-61 | 75.43 |
| 210°F | | D 445-61 | 16.80 |
| 500°F | EXT. | | 1.75 |
| Viscosity Index | | D 567-53 | 108 |
| Pour Point | | D 97-57 | +16°F |
| Flash Point | | D 92-57 | 510°F |
| Fire Point | | D 92-57 | 552°F |
| Color (Union) | | D1500-58T | 6 Minus |
| Specific Gravity 60°F | | None | 0.8709 |
| Evaporation Loss (22 hrs. @250°F) | | D 972-56 | 0.30% |
| Galvanic Corrosion (10 days, 80°F, Relative Humidity 50%) | | Federal Test Method No. 791a | Failed Evidence of corrosion and pitting on test specimens. |
| Humidity Cabinet (100 hrs. 100% Relative Humidity, 120°F) | | D1748-60T | Failed Test specimens corroded. |

## Corrosivity Test
## Corrosiveness and Oxidation

| | | | |
|---|---|---|---|
| Copper, | change | $MG/CM^2$ | .0003 |
| Steel, | change | $MG/CM^2$ | .0002 |
| Aluminum, | change | $MG/CM^2$ | .0002 |
| Magnesium, | change | $MG/CM^2$ | .0001 |
| Cadmium, | change | $MG/CM^2$ | .0003 |

Copper visible corrosion - No corrosion - slight discoloration
Steel visible corrosion - No corrosion - slight discoloration
Aluminum visible corrosion - No corrosion - slight discoloration
Magnesium visible corrosion - No corrosion - slight discoloration
Cadmium visible corrosion - No corrosion - slight discoloration

Weight loss resulting from evaporation of test oil - None
Appearance of test oil after test - Dark and Cloudy
Viscosity after test 130°F 77.74 centistokes
Viscosity increase after test 3.06%

### Oil Contamination Analysis

Number of particles per 25 ML. $0.12 \times 10^6$

Largest particle 15 microns

---

## Physical Properties

| | | Test Method A.S.T.M. | New Departure Gyro Oil "G" Filtered through 15 micron Filter Physical Properties Determined August and September 1964 |
|---|---|---|---|
| Viscosity, Centistokes | | | |
| -65°F | EXT. | | 15,000,000. |
| -40°F | EXT. | | 700,000. |
| 0° | EXT. | | 20,500. |
| 100°F | | D 445-61 | 176.14 |
| 130°F | | D 445-61 | 75.10 |
| 210°F | | D 445-61 | 17.26 |
| 500°F | EXT. | | 1.78 |
| Viscosity Index | | D 567-53 | 110 |
| Pour Point | | D 97-57 | +16°F |
| Flash Point | | D 92-57 | 510°F |
| Fire Point | | D 92-57 | 552°F |
| Color (Union) | | D1500-58T | 6 Minus |
| Specific Gravity 60°F | | None | 0.8709 |
| Evaporation Loss (22 hrs, @250°F) | | D 972-56 | 0.30% |
| Galvanic Corrosion (10 days, 80°F, 50% Relative Humidity) | | Federal Test Method No. 791a | Failed Evidence of corrosion & pitting on test specimens |
| Humidity Cabinet (100 hrs. 100% Relative Humidity 120°F) | | D1748-60T | Failed Test specimens corroded |

Corrosivity Test
Corrosiveness and Oxidation

| | | | |
|---|---|---|---|
| Copper, | change | $MG/CM^2$ | .0005 |
| Steel, | change | $MG/CM^2$ | .0001 |
| Aluminum, | change | $MG/CM^2$ | .0002 |
| Magnesium, | change | $MG/CM^2$ | .0000 |
| Cadmium, | change | $MG/CM^2$ | .0002 |

Copper visible corrosion - No corrosion - slight discoloration
Steel, visible corrosion - No corrosion - slight discoloration
Aluminum visible corrosion - No corrosion - slight discoloration
Magnesium visible corrosion - No corrosion,- slight discoloration
Cadmium visible corrosion - No corrosion - slight discoloration

Weight loss resulting from evaporation of test oil - None
Appearance of test oil after test - Dark and Cloudy'
Viscosity after test 130°F 77.52 centistokes
Viscosity increase after test 3.22%

Oil Contamination Analysis

Number of particles per 25 ML. $0.29 \times 10^6$

Largest particle 20 microns

Particle contamination analysis was conducted in accordance with Standard Procedure ST-100.

A sample of Dr. Klaus lubricant MLO-7670 which was originally scheduled to be part of this test program could not be obtained by Mr. Pierry.

Infra-red analysis on the subject oils were submitted to Mr. Pierry prior to this report.

Metallurgy & Chemistry Dept.

F. Rodriguez
F. Rodriguez

Approved by: [signature]

FR/mr

SECTION 5.3

FREQUENCY SPECTRUM & SAMPLE
FREQUENCY GAIN PLOT

## FREQUENCY SPECTRUM

| Defect or Lobe $\omega$ | $f_o$ cps | $f_i$ cps | $f_{o(sub)}$ cps | $f_{i(sub)}$ cps |
|---|---|---|---|---|
| 1 | 1064 | 1736 | 400 | 0 |
| 2 | 2128 | 3472 | 666 | 1736 |
| 3 | 3192 | 5208 | 666 | 1736 |
| 4 | 4256 | 6944 | 1464 | 1736 |
| 5 | 5320 | 8680 | 2528 | 3472 |
| 6 | 6384 | 10416 | 666 | 1736 |
| 7 | 7448 | 12152 | 96-400 | 0-496 |
| 8 | 8512 | 13888 | 1464 | 1736 |
| 9 | 9576 | 15624 | 3856 | 6944 |
| 10 | 10640 | 17360 | 2792 | 5208 |
| 11 | 11704 | 19096 | 3392 | 5208 |
| 12 | 12768 | 20832 | 5720 | 8680 |
| 13 | 13832 | 22568 | 2704 | 3472 |
| 14 | 14896 | 24304 | 56-552 | 248-744 |
| 15 | 15960 | 26040 | 2528 | 3472 |

Ball spin about its axis = 691.5 cps

Calculations

$$N_E = N_o(1/2)\left[1 + {}^{d}/_{E}\cos B\right]$$
$$= 248 \text{ cps}$$

$$f_o = \left(\frac{n}{2}\right)\left(\frac{N_o}{Q}\right)\omega\left[1 - {}^{d}/_{E}\cos B\right] = 1064\,\frac{\omega}{Q}$$

$$f_i = \left(\frac{n}{2}\right)\left(\frac{N_o}{Q}\right)\omega\left[1 + {}^{d}/_{E}\cos B\right] = 1736\,\frac{\omega}{Q}$$

$$f_{o(sub)} = \left[\frac{N_o}{2}\cdot\frac{\omega}{Q}K \pm \frac{1 + {}^{d}/_{E}\cos B}{1 - {}^{d}/_{E}\cos B}\right]\left(1 - {}^{d}/_{E}\cos B\right)$$

$$= 152\,\frac{\omega}{Q} \pm 248$$

$$f_{i(sub)} = \frac{N_o}{2}\left[\frac{\omega}{Q}K \pm 1\right]\left(1 + {}^{d}/_{E}\cos B\right)$$

$$= 248\,\frac{\omega}{Q} \pm 248$$

$N_E$ = $\omega_p$ of pitch dia.
= 248 cps

$N_o$ = $\omega_o$ of outer race
= 400 cps

$\cos B = \cos 28^\circ = .8829$

$1 + \square = 1.240$

$1 - \square = .760$

$\dfrac{1+\square}{1-\square} = 1.63$

$\omega$ = defect or lobe

$n$ = # balls

$Q$ = # balls in simultaneous contact

$K$ = ball space/lobe

ENGINEERING TEST INSTRUCTION

E.T.I. 3.0

SATURN AB-5 AND AMAB-3

BEARING NOISE ANALYSIS

REVISED: 2/24/67

REF. E.T.O. 4537

Prepared by: Louis J. Tomaselli
Vibration Laboratory

Approved by: [signature]
Ass't Chief Engineer

Approved by: [signature] T. Demkow
Engineering Test

K+E SEMI-LOGARITHMIC 3 CYCLES X 70 DIVISIONS
KEUFFEL & ESSER CO. MADE IN U.S.A.



THE Bendix CORPORATION
ECLIPSE-PIONEER DIVISION • TETERBORO, NEW JERSEY

# AB-5 GYRO MOTOR NOISE ANALYSIS

GYRO AXIS
☐ ⊥ TO SPIN AXIS
☒ II TO SPIN AXIS

SERIAL NUMBER M-215CCM15

ENGINEERING TEST

ETO NO.

FILTER 50 Hz BW

RANGE 0.1VRMS

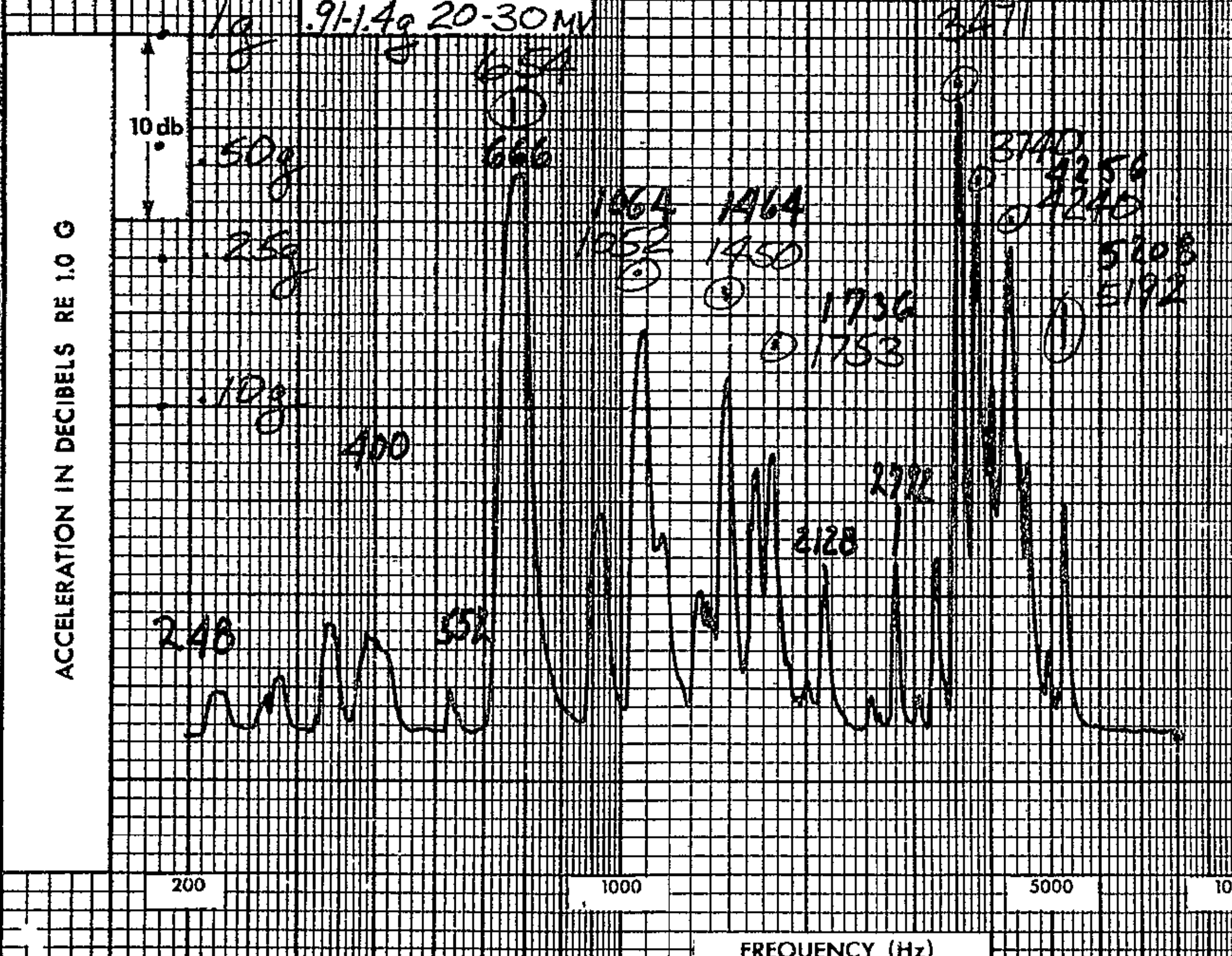
CAPACITANCE 60 uf

SWEEP 0.150 dec/min

ACCELEROMETER S/N 304

CONSTANT 22.0 mv/g PK

TOTAL G's Tot. Sig. .91-1.4g 20-30MV




| Wa | | Wc | |
|---|---|---|---|
| 1 | 400 s.b. 1664 F | 1 | 1736 F |
| 2 | 666 s.b. 2128 F | 2 | 1736 s.b. 3472 F |
| 3 | 666 s.b. | 3 | 1736 s.b. 5208 F |
| 4 | 1464 s.b. 4256 F | 4 | 1736 s.b. |
| 5 | — | 5 | — |
| 6 | 666 s.b. | 6 | 1736 s.b. |
| 7 | 400 s.b. | 7 | — |
| 8 | 1464 s.b. | 8 | 1736 s.b. |
| 9 | — | 9 | — |
| 10 | 2792 s.b. | 10 | 5208 s.b. |

FIGURE ____________

DATE 10-19-68

TIME

TEST ENGINEER RGO

## 1.0 General

1.1 Test Purpose and Method - This test procedure pertains to the Saturn Gyro Motors AB-5 and AMAB-3. The purpose of this test is to determine the mechanical noise characteristics of the motors at constant speed and during rundown. The noise is a result of vibration induced by the gyro motor and/or bearings. This is accomplished by recording the output of a piezoelectric accelerometer mounted to the top of the motor run-in fixture. Mounting is accomplished by (3) three #4 screws. Recordings of the response will be made parallel to the spin axis of the motor and perpendicular to spin axis of the motor. See Figure 2 for accelerometer and axis orientation.

1.2 Facility - Central Station Data Analysis Instrumentation.

1.3 Test Equipment - Columbia Tri-Axial accelerometer and instrumentation as shown in Figures 2 and 6.

## 2.0 Installation

2.1 The Gyro Laboratory personnel will install the Gyro in the run-in fixture and make all necessary electrical connections from the Gyro to the test fixture. The toggle valve on the test fixture must not be opened. Fixtures with the toggle valve taped in the closed position are AB-5's and contain helium. If this toggle valve is opened, the Gyro is not to be tested. Return Gyro to Gyro Laboratory. The fixtures with toggle valves not taped contain air and can be tested if the toggle valve is opened.

CAUTION: Do Not Open Toggle Valves On Test Fixtures.

The Vibration Laboratory Test Engineer will be responsible for the installation of the adapter, the accelerometer and attaching cable as indicated in Figure 2. He will also install the necessary power requirements of 26VAC, 400 cycle, 3 phase power to the Gyro. The 3 phase power from the wall plug is wired to a knife switch which has a protective fuse in each phase. Leads from the knife switch to the Gyro test fixture must be connected in the following manner:

2.0 <u>Installation</u> - Cont'd

2.1 Phase A from switch to brown lead on fixture.
Phase B from switch to red-white-yellow-green on fixture.
Phase C from switch to red lead on fixture.

<u>CAUTION</u>: Lead from switch and lead on fixture will not be the same color.

3.0 <u>Calibration Constant Speed Analysis</u>

3.1 <u>General</u>

a) Set the accelerometer sensitivity at 100 mv/G by means of the Glennite Amplifier and Cathode Follower.

b) Use 50 cycle bandpass filter in the SD-101 Analyzer and calibrate analyzer according to the analyzer manual. Use DC output and a 60uf damping capacitor.

c) Adjust tuning signal on SD-1012 Analyzer as required.

d) Range switch on SD-1012 Analyzer set at 0.5 volts (R.M.S.)

e) Use a Krohn-Hite Ultra-Low Frequency Band-Pass Filter with a Low Cutoff Frequency of 100 cps, and a High Frequency Cutoff of 4500 cps. High-low switch on low.

f) Check Ballantine 320 VTVM using internal calibration signal.

g) Calibrate X-Y plotter:

1) <u>X Axis</u> - Set 200cps and 10KC on sweep oscillator - read frequency on EPut meter - adjust plotter as necessary. Check 500 and 2000cps points making sure of the linearity of the sweep. Oscillator Settings Multiplier A on 10, Multiplier B on 1, Log Sweep on Single, Function Sine Wave.

3.0 Calibration Constant Speed Analysis - Cont'd

3.1 General

g) Calibrate X-Y plotter:

2) Y Axis - Set Log Voltage Converter for a scale factor of 10db/inch - attenuation switch on 10 and switch on DC. Adjust Y Axis of plotter to read 1.0G on the 3 cycle semi-logarithmic graph paper (Figure 1) for a reference point. Check attenuation scale - 10db. Touch pen to paper to indicate 1.0, 0.5, 0.25, and 0.10 "G" level at 200cps. And at 5,000cps use Oscillator Voltage to set these levels.

4.0 Test Procedure Constant Speed Analysis

4.1 General

1) Prior to starting test an amplitude response curve must be run to a comparison check of the Cathode Follower and Amplifier. This is accomplished in the following manner: Apply 50 MV input signal to the Cathode Amplifier with instrumentation as shown in Figure 3. The output signal of the Gulton Amplifier must be read on a VTVM and recorded. Run sweep from 200 cps to 10KC. This response curve must be repeated after the last Gyro has been tested.

2) With instrumentation as shown in Figure 2, attach accelerometer cable to Y Axis of the pickup and to the Cathode Follower and Amplifier. Read and record system noise level.

3) Close knife switch energizing Gyro. Allow 2-3 minutes for motor to synchronize.

4) Set Oscillator Sweep rate dial to a reading of .150 $\frac{dec}{min}$. This is approximately a fifteen (15) minute sweep from 200cps to 10KC.

5) Turn Servo switch on X-Y plotter to "ON". With sweep oscillator set at 200 cps, EPut meter reading 200 cps, the X-Y plotter pen should indicate 200cps. If the three (3) instruments do not agree, repeat 3.3.1, step f.

CAUTION: Do not run motor more than 30 minutes at any one time.

## 4.0 Test Procedure Constant Speed Analysis - Cont'd

### 4.1 General

6) Push "sweep up" button on oscillator, at the same time move the X-Y plotter switch marked "PEN" to the "down" position. Monitor the frequency on the EPut meter. Note total signal on VTVM.

7) Upon reaching the 10KC, the end of the sweep, move the "PEN" switch to the "UP" position. The oscillator will automatically stop at 10KC.

8) Repeat steps 2 thru 6 changing the accelerometer cable to the Z axis of the Columbia Tri-Axial accelerometer.

## 5.0 Shut Down Procedure

5.1 Emergency - Vibration analysis shall be interrupted at any time before or during the sweep if any abnormality or abnormal response occurs. This can be accomplished by pushing the "HOLD" button on the sweep oscillator and by moving the pen switch on the X-Y plotter to the "UP" position. Investigate the cause of the trouble and correct.

CAUTION: Do not operate motor more than 30 minutes at any one time.

5.2 Normal - Follow this sequence of operations.

1) Move pen switch on X-Y plotter to the "UP" position. Shut off Servo switch on X-Y plotter.

2) Open knife switch, de-energizing Gyro.

## 6.0 Calibration - Rundown Analysis

### 6.1 General

a) Remove the following inputs in rear of test stand.

1. Log Converter

2. Beckman E-Put Meter

3. X-Axis of X-Y Plotter

b) Adjust Krohn-Hite Band Pass Filter for a low cut-off frequency of 2cps and a high frequency cut-off at 400cps.

c) Re-calibrate SD104-S sweep oscillator between 10 and 400cps, reading frequency on E-Put Meter.

d) Use 5 to 5,000 cps discriminator module in the Log Frequency Converter with the filter select on 5cps.

e) Calibrate X-Y Plotter

1. X-Axis - With the instrumentation hooked-up as shown in Figure 5, adjust plotter for the frequency limits set on the sweep oscillator (10-400cps). The output voltage from the sweep oscillator must be equal to or greater than 500MV to comply with the input requirements of the Log Frequency Converter. Use the 100MV output terminal on the Log Frequency Converter. Use 3 cycle semi-logarithmic graph paper as shown in Figure 4.

2. Y-Axis - Set Log Voltage Converter for a scale factor of 10 db/inch - attenuation at 0 db and source switch on AC. With instrumentation hooked-up as shown in Figure 5, adjust plotter and mark calibration points on graph paper for MV equivalancies of 1G, .5G, .25G and .1G at 400 cps.

## 7.0 Test Procedure - Rundown Analysis

### 7.1 General

a) Hook-up instrumentation as shown in Figure 6.

b) Set B & K Voltmeter (amplifier) on the 10 db scale with meter switch on rms undamped.

c) Set H/P oscilloscope vertical sensitivity at 1 volt/cm and horizontal at .5 millisec/cm. (The latter will vary with changing frequency).

d) Use input B (front input) on E-Put Meter with attenuation setting AC 10.

e) Energize the gyro by closing the knife switch (if fuse blows on knife switch, reverse the alligator clips on the end terminals of the 3 phase power terminal strip) and allow two (2) minutes for the gyro motor to reach synchronous speed (400cps)

f) Note that the pen on the X-Y plotter is at 400 cps and approximately at the 1 "G" level. Put the pen down and open the knife switch.

g) Monitor the oscilloscope on the 1 volt/cm vertical scale. When the P-P signal drops down to approximately 5 cm with decreasing motor RPM increase the gain on the B & K voltmeter (amplifier) by 10 db. The DB Range will be from 10 to -40 in steps as determined by the aforementioned signal on the oscilloscope. This is a general guide line and does not have to be followed exactly.

h) When the gyro motor speed approaches 4 cps the pen should be put in the "PEN-UP" position.

## 8.0 Shut Down Procedure

### 8.1 Normal - Follow this sequence of operations:

1) Shut off servo switch on X-Y plotter.

2) Remove power leads from test fixture. Remove accelerometer and adapter.

9.0 Unit Disposition

9.1 Place Gyro in the Vibration Laboratory Test Equipment Cabinet. Gyro Laboratory personnel will pick it up.

10.0 Data

10.1 Log Sheets

Record on the log sheets the following information.

1) Date of test.
2) Facility operated.
3) Unit name, model and serial number.
4) E.T.O. number.
5) Engineering project number.
6) Test time - start and stop.
7) Unit energized.
8) Accelerometer serial number, constants for each axis.
9) Amplifier serial number and its setting.
10) Gyro axis (A axis perpendicular to spin axis)
    (B axis parallel to spin axis)
11) Plot number and accelerometer axis.
12) Total "G;s" of Gyro noise.
13) Noise level, Gyro not energized.
14) Bandpass filter S/N and settings.

10.2 Record on each Harmonic Analysis Plot the following.

1) E.T.O. number.
2) Gyro serial number.
3) Test Axis of Gyro.
4) Total "G's".
5) Sweep time - dec/min.
6) Capacitance.
7) DB scale factor.
8) Bandwidth and Bandwidth Filter S/N.
9) Date.
10) Figure number.
11) Calibration Reference Points 1.0G, 0.5G, 0.25G, and 0.10G.
12) Accelerometer S/N and constant.
13) Analyzer range setting.
14) Filter response curve.
15) Calibration 100mv/G.

10.3 Engineering Test Summary Report - Fill in all required information.

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GYRO MOTOR NOISE ANALYSIS

GYRO AXIS ☐ ⊥ TO SPIN AXIS ☐ ‖ TO SPIN AXIS

SERIAL NUMBER

| ENGINEERING TEST | ETO. NO. 4537 |
|---|---|
| FILTER ______ Hz BW | |
| RANGE | CAPACITANCE ______ uf |
| SWEEP ______ dec/min | ACCELEROMETER S/N |
| CONSTANT ______ mv/g PK | |

TOTAL G's

ACCELERATION IN DECIBELS RE 1.0 G

10 db

200 1000 5000 10000

FREQUENCY (Hz)

| FIGURE ______ | DATE | TIME | TEST ENGINEER |
|---|---|---|---|
| | | | |

FORM 13962 NS

# SATURN GYRO MOTOR MODELS AB-5 & AMAB-3

## INSTRUMENTATION SET-UP

E.T.I. 3

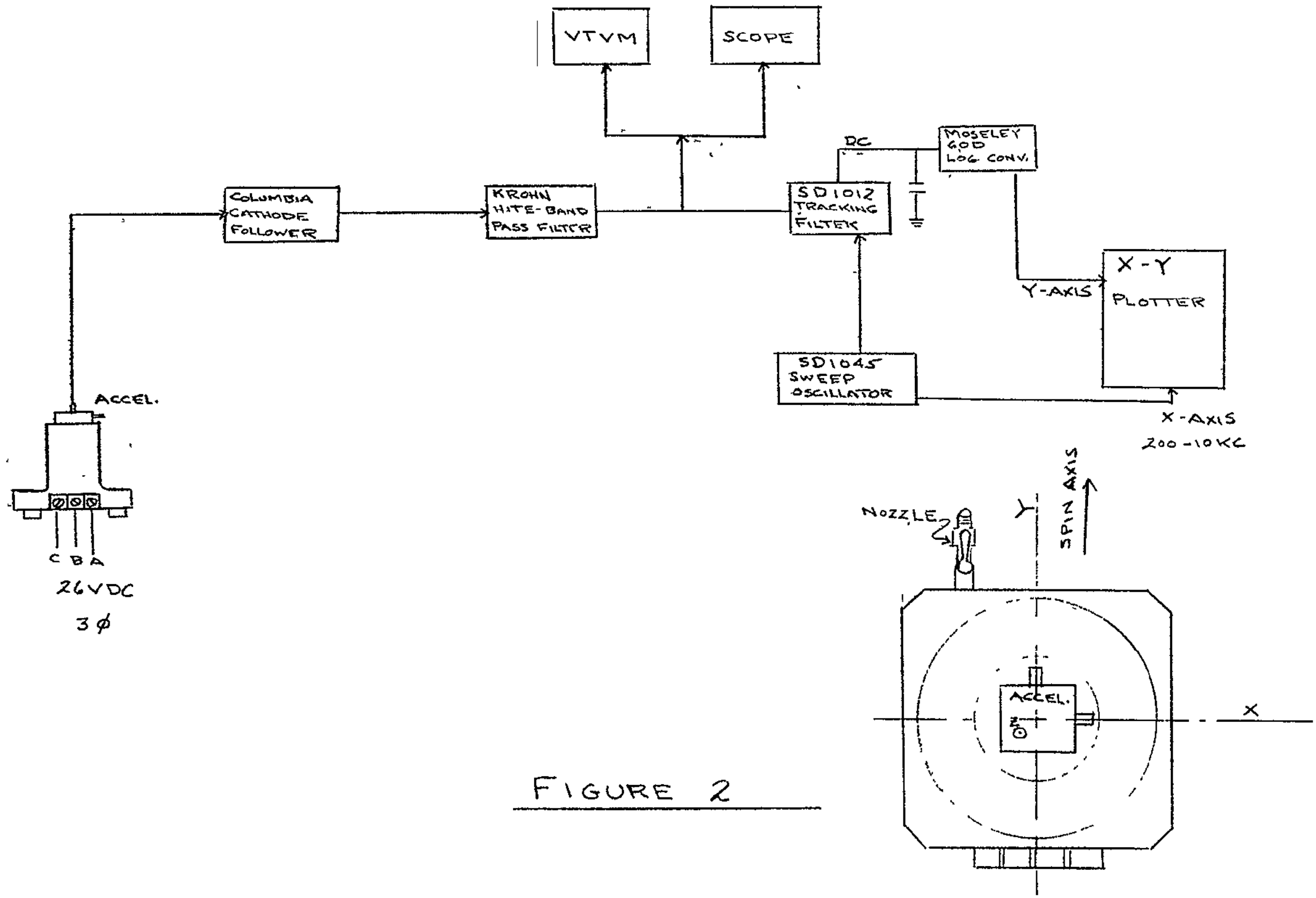


FIGURE 2

## AMPLIFIER RESPONSE CURVE SET-UP

ETI 3.

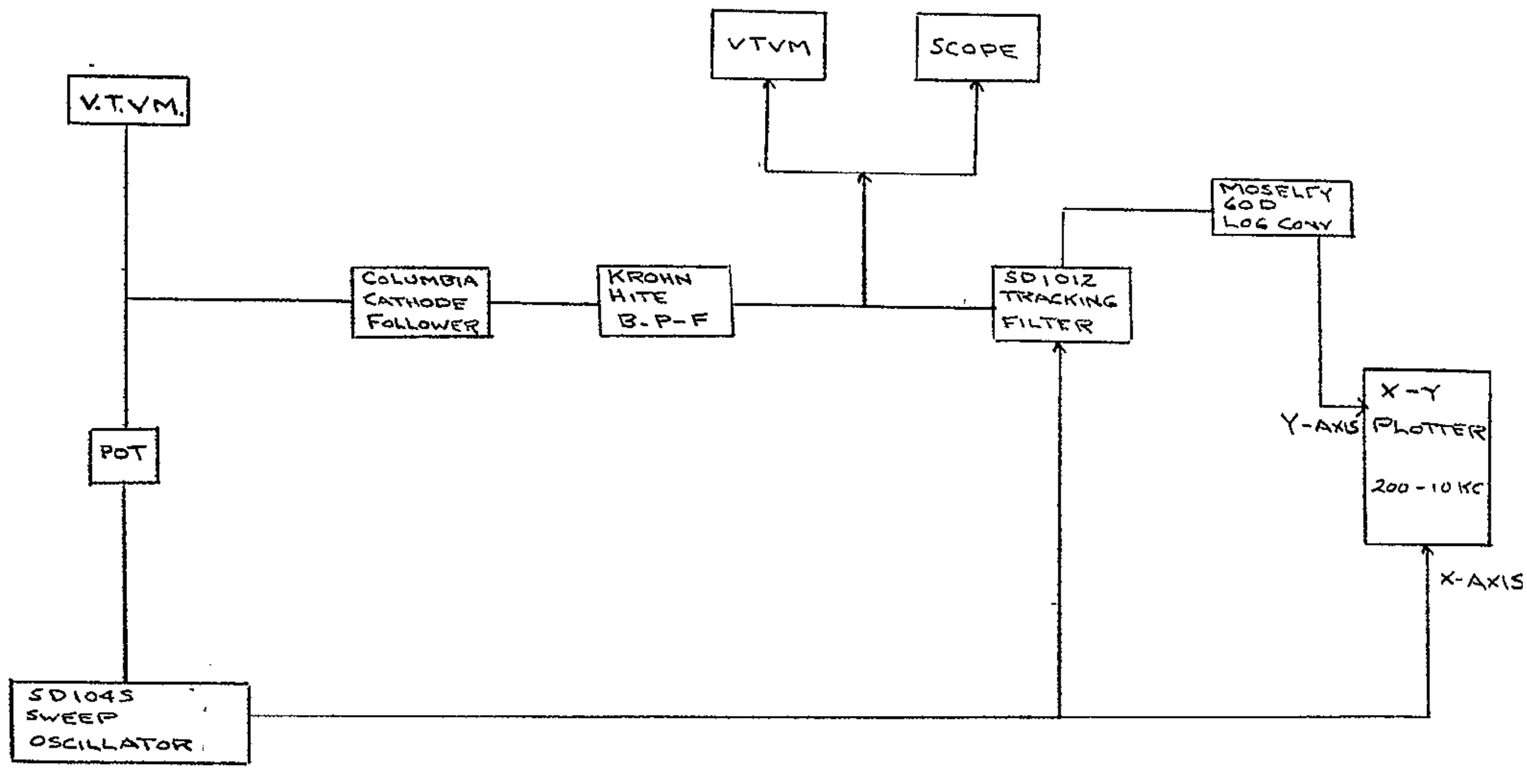


FIGURE 3

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TOTAL G's

## GYRO MOTOR NOISE ANALYSIS

GYRO AXIS
☐ ⊥ TO SPIN AXIS
☐ ∥ TO SPIN AXIS

SERIAL NUMBER

| ENGINEERING TEST | ETO. NO. 4537 |
|---|---|
| FILTER ______ Hz BW | |
| RANGE | CAPACITANCE ______ uf |
| SWEEP ______ dec/min | ACCELEROMETER S/N |
| CONSTANT ______ mv/g PK | |

10 db

ACCELERATION IN DECIBELS RE 1.0 G

200 1000 5000 10000

FREQUENCY (Hz)

FIGURE ______

| DATE | TIME | TEST ENGINEER |
|---|---|---|
| | | |

THE BENDIX CORP

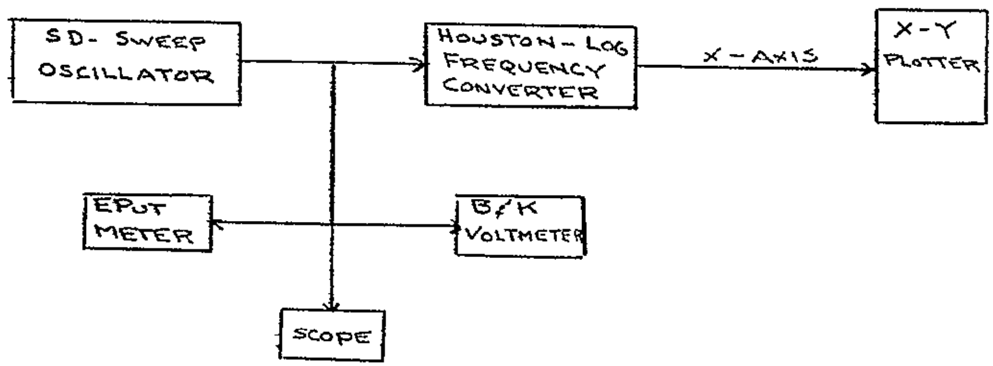
NAVIGATION AND CONTROLS DIV.

SATURN GYRO MOTOR MODELS AB-5 & AB-3 RUNDOWN ANALYSIS

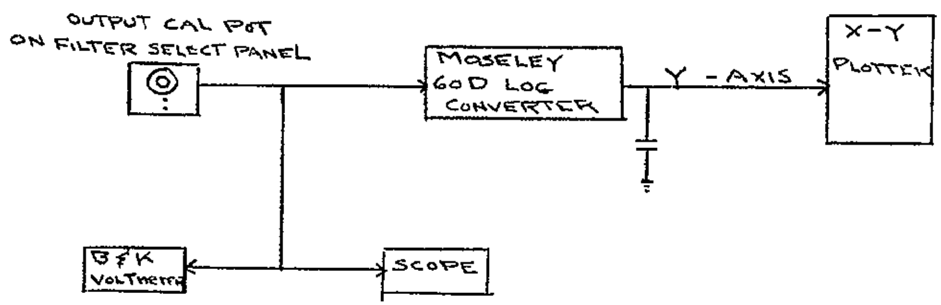
# CALIBRATION

## INSTRUMENTATION SET UP

ET.1 3.




X - AXIS




Y - AXIS

## SATURN GYRO MOTOR MODELS AB-5 & AB-3 RUNDOWN ANALYSIS

## TEST

## INSTRUMENTATION SET UP

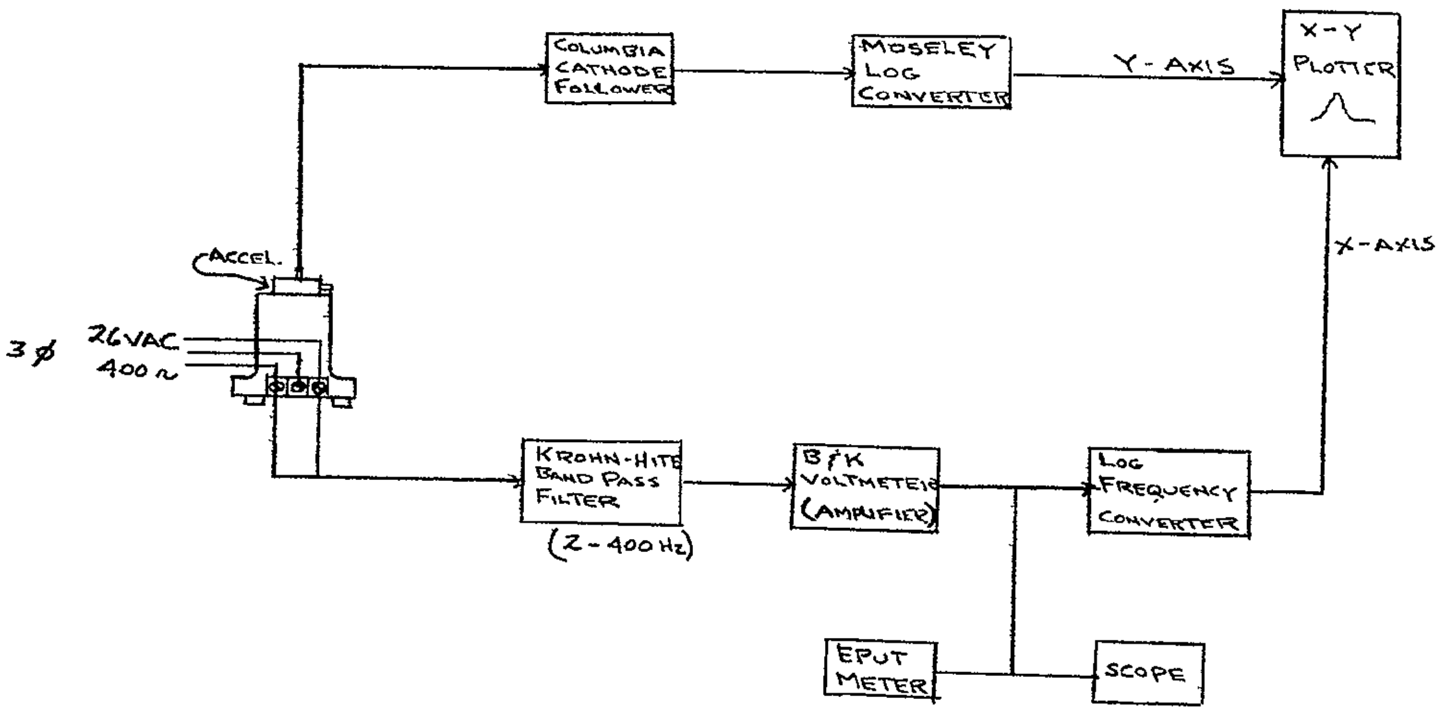
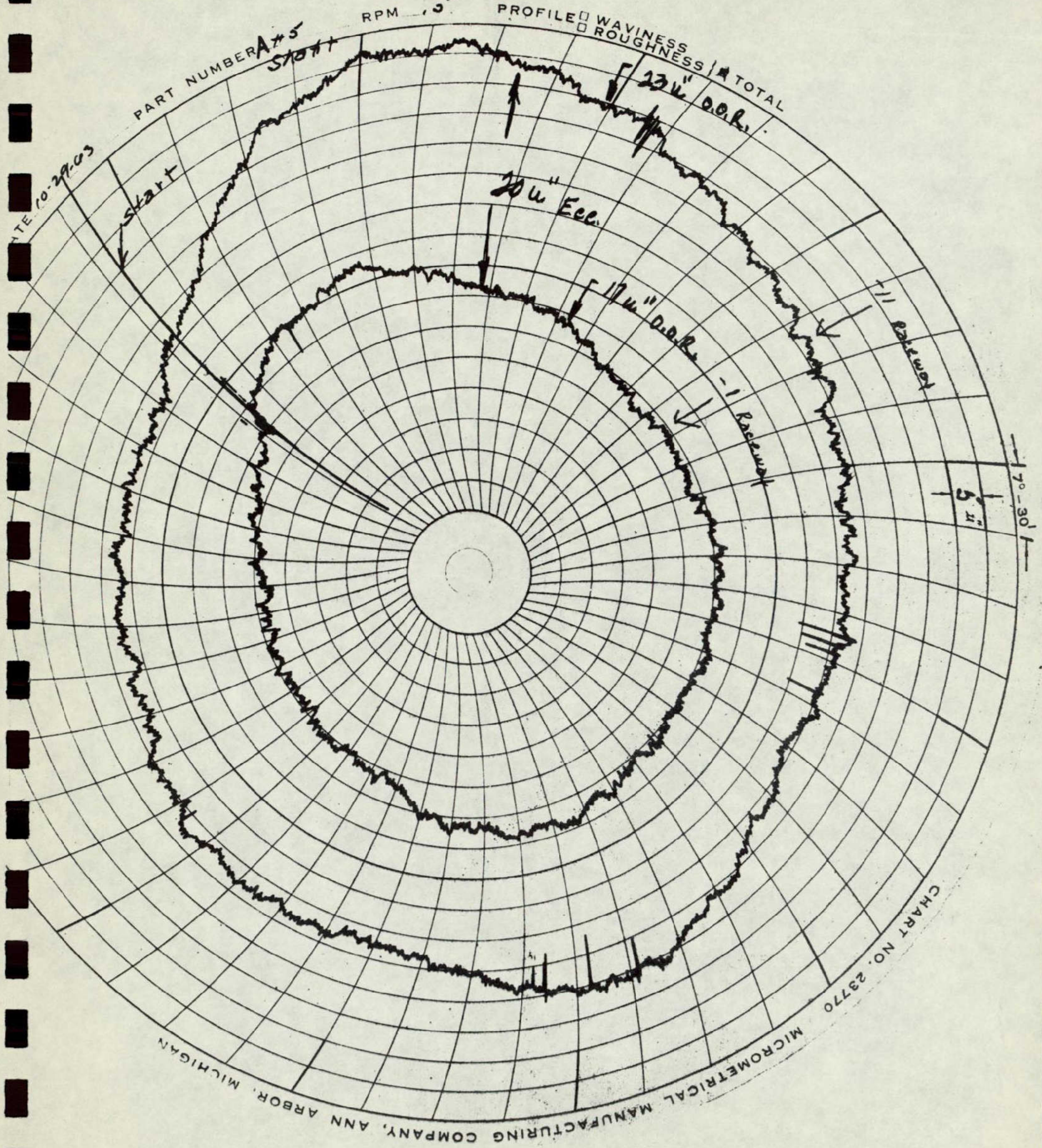


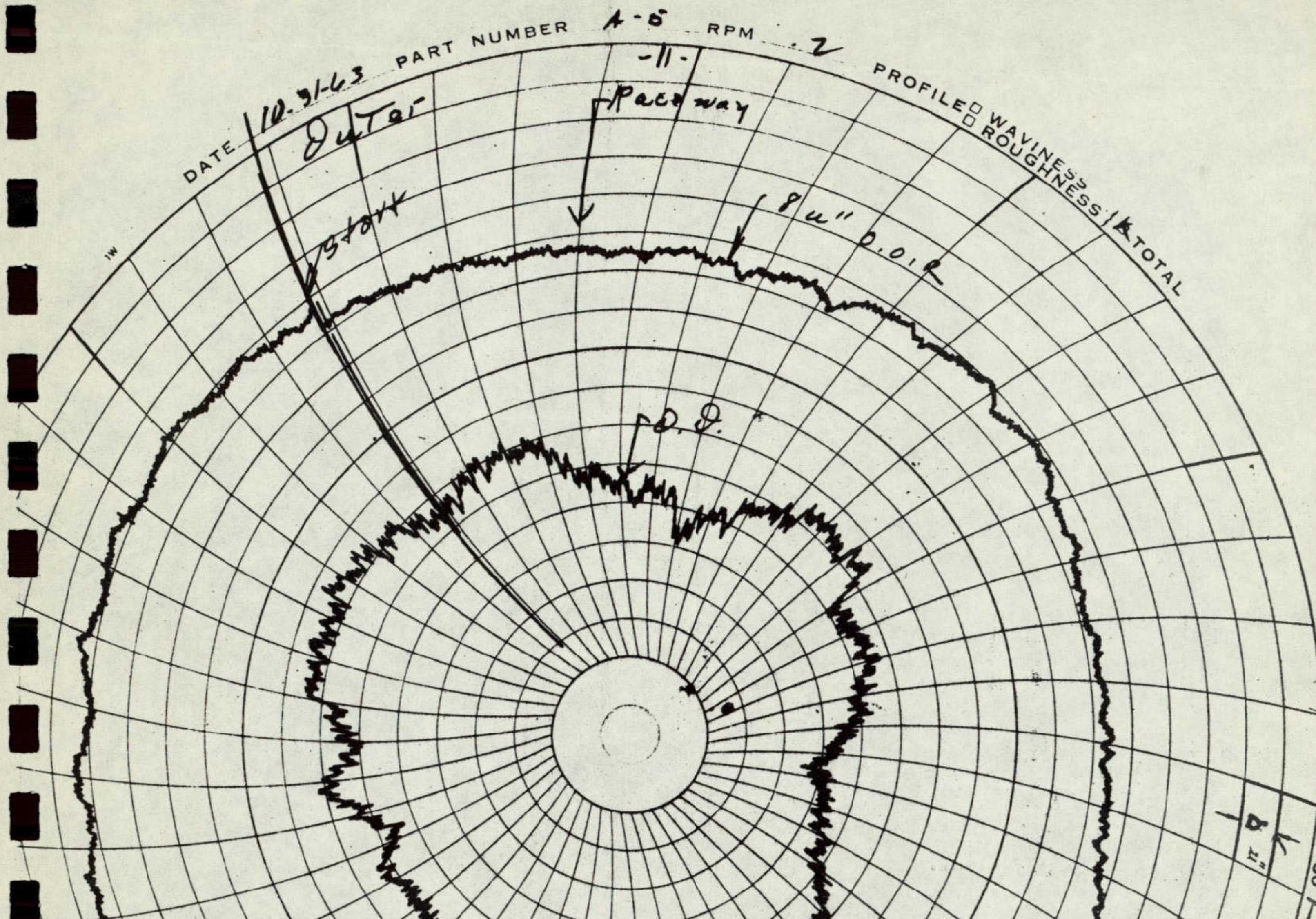

FIGURE 6

## SECTION 5.4

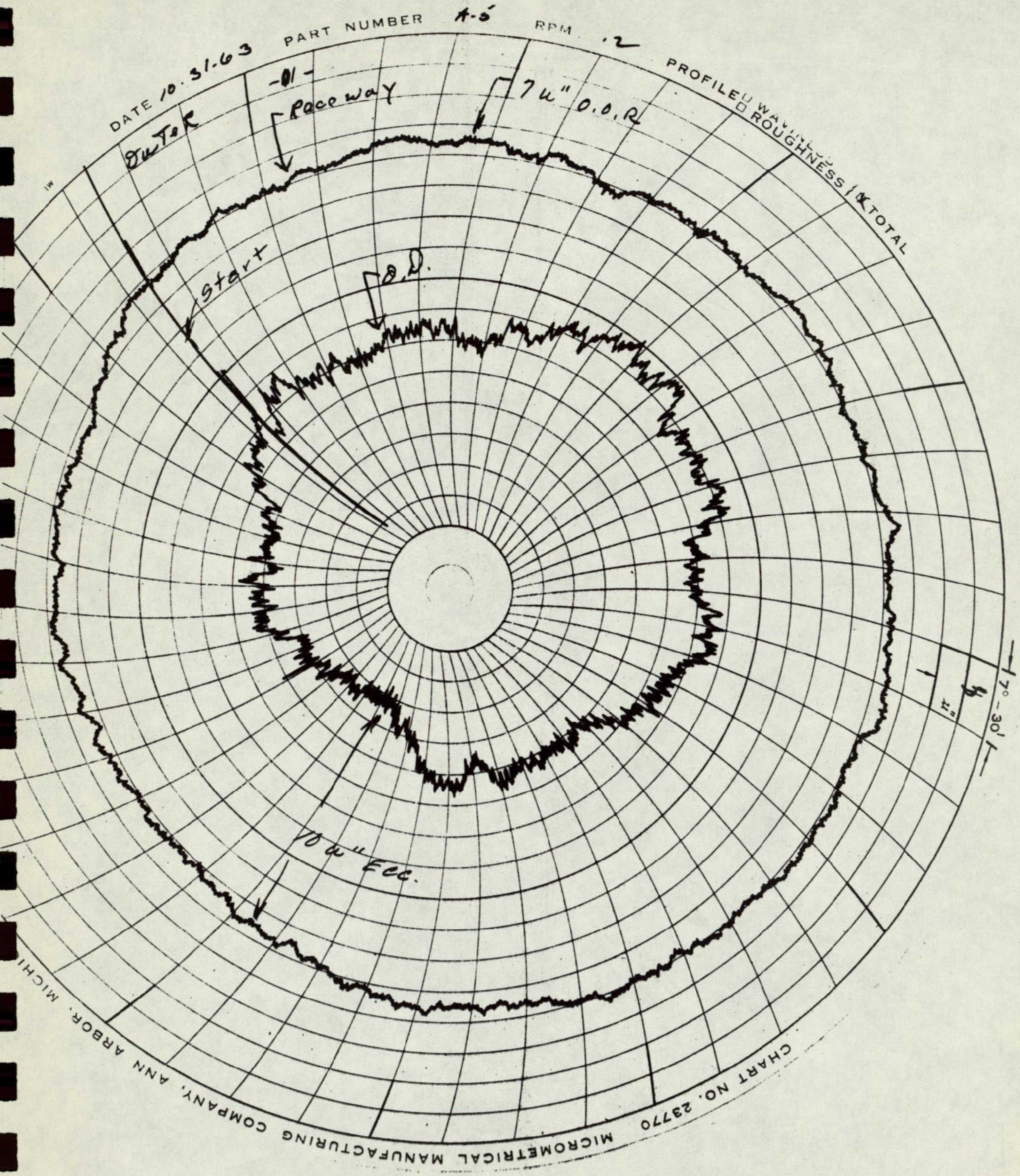
## SURFACE FINISH PICTURES AND PROFICORDER CHARTS



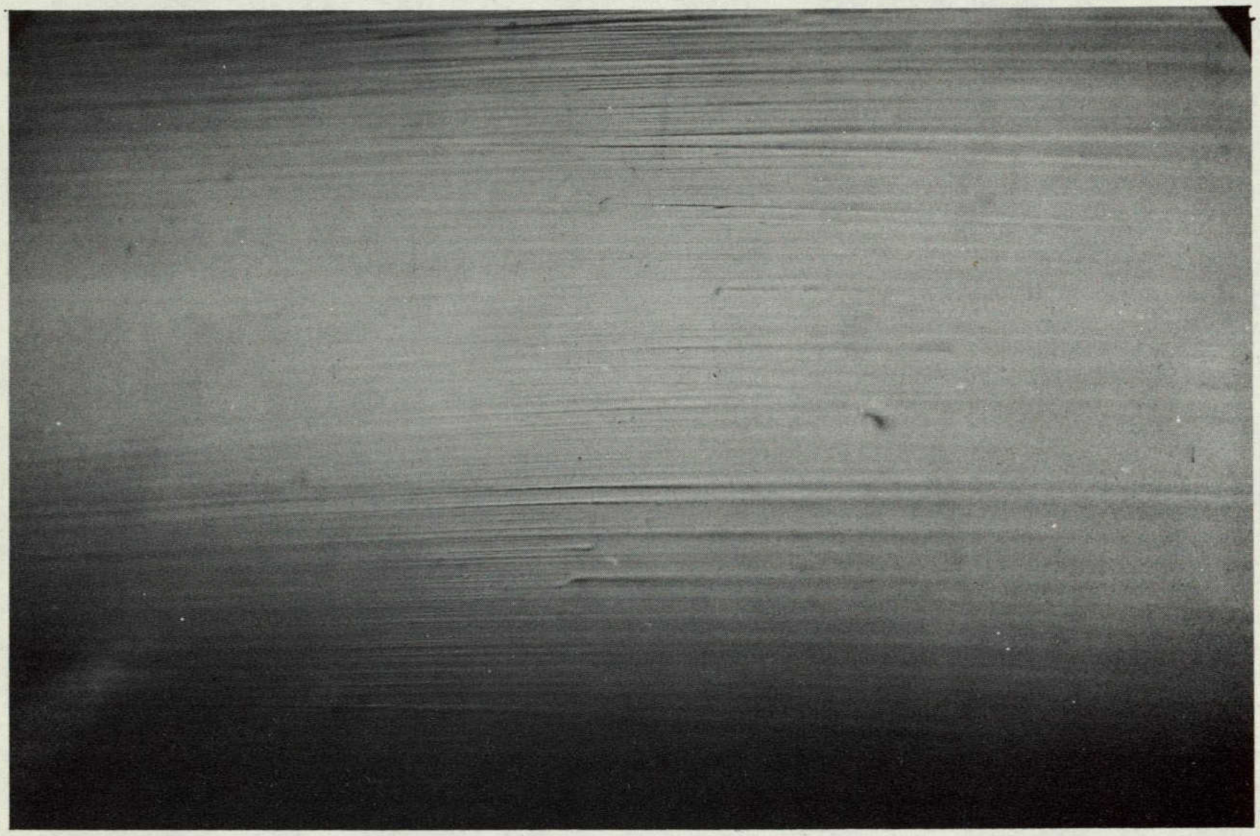

PROFICORDER TRACES OF INNER RACE OF LOT A , BRG. 5




PROFICORDER TRACES OF OUTER RACE OF LOT A , BRG. 5



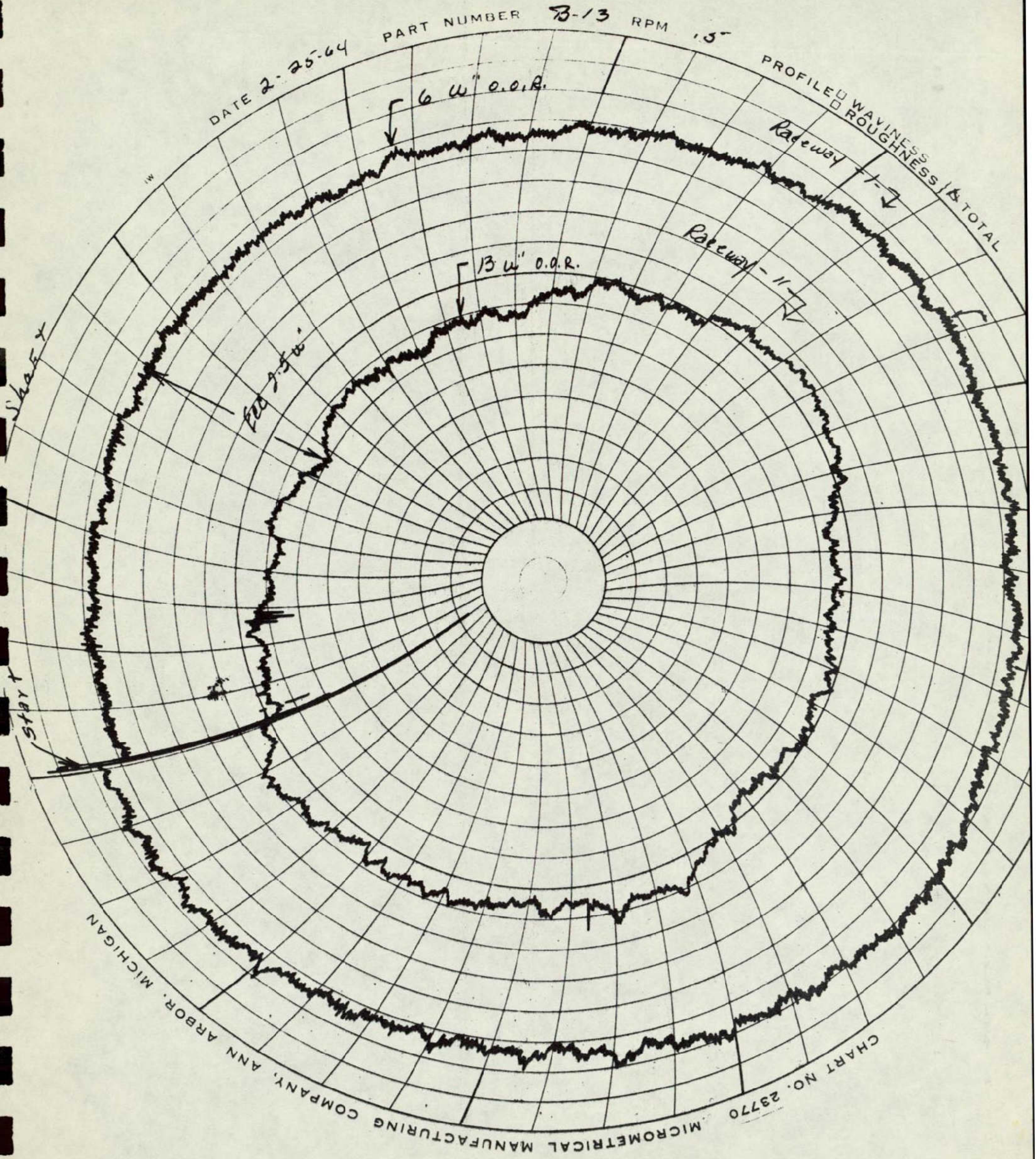

PROFICORDER TRACES OF OUTER RACE OF LOT A , BRG. 5



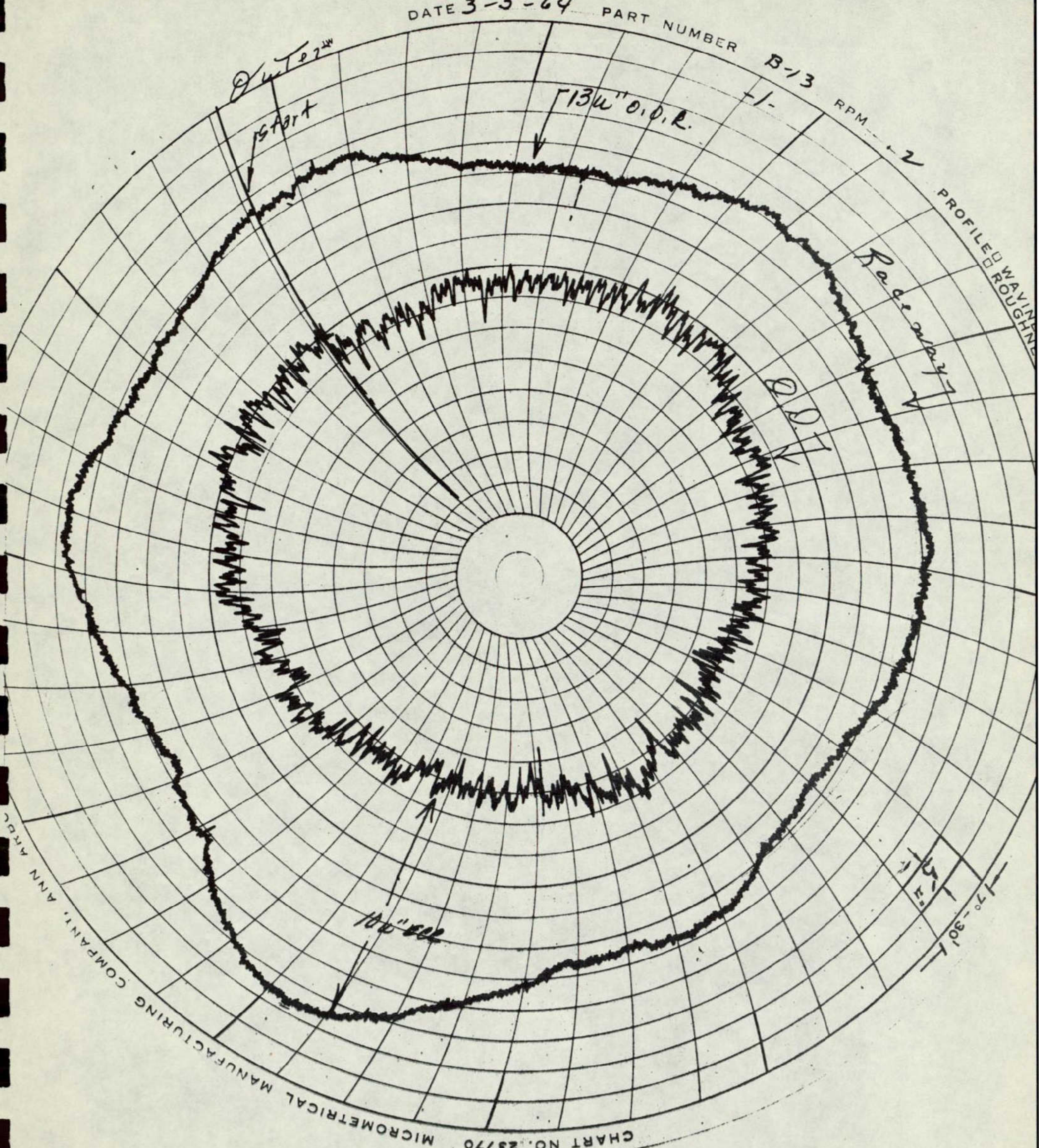
MRC B 13

Shaft #2 Side 250 X

Phase II




PROFICORDER TRACES OF INNER RACE OF LOT B , BRG. 13

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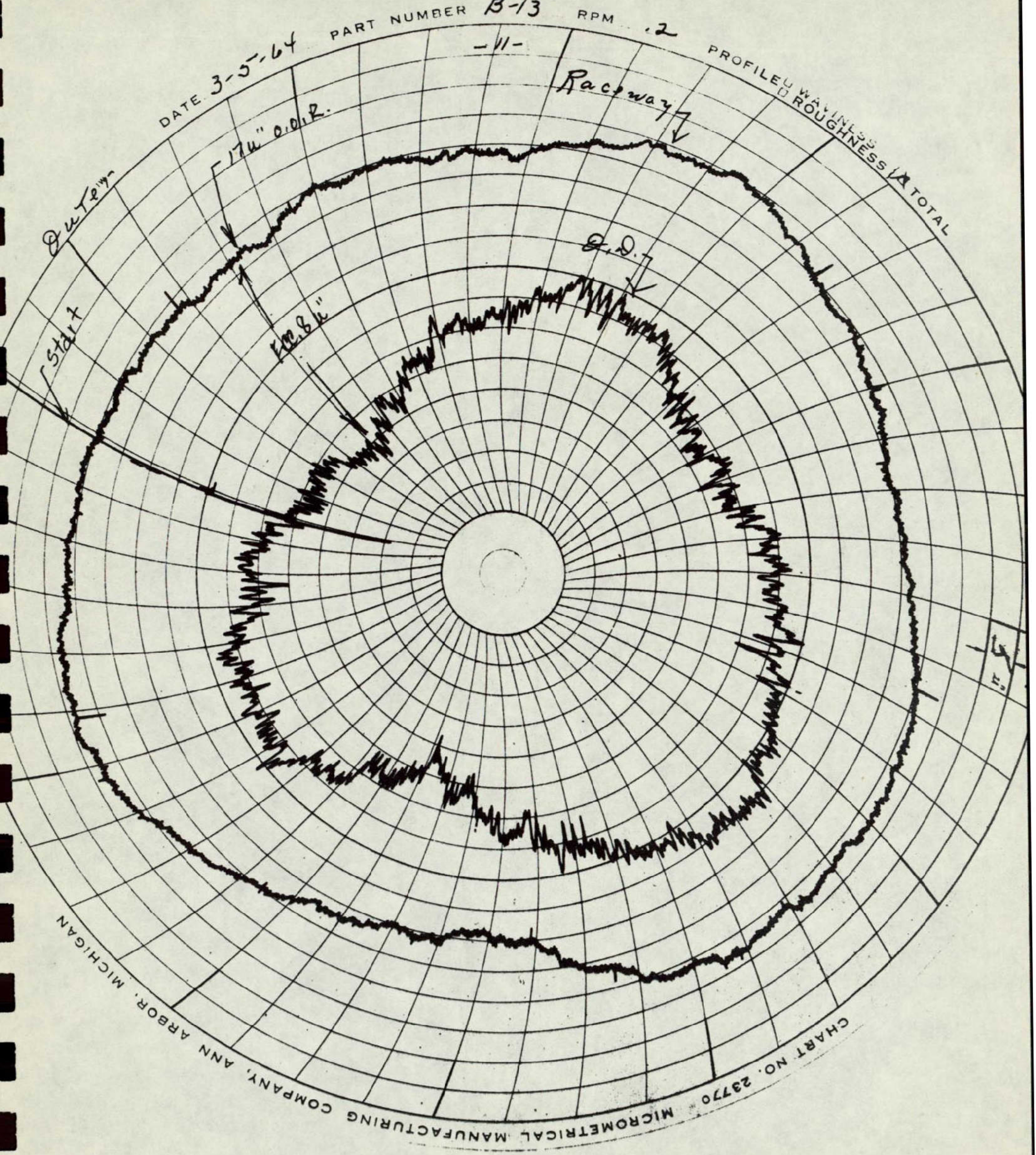


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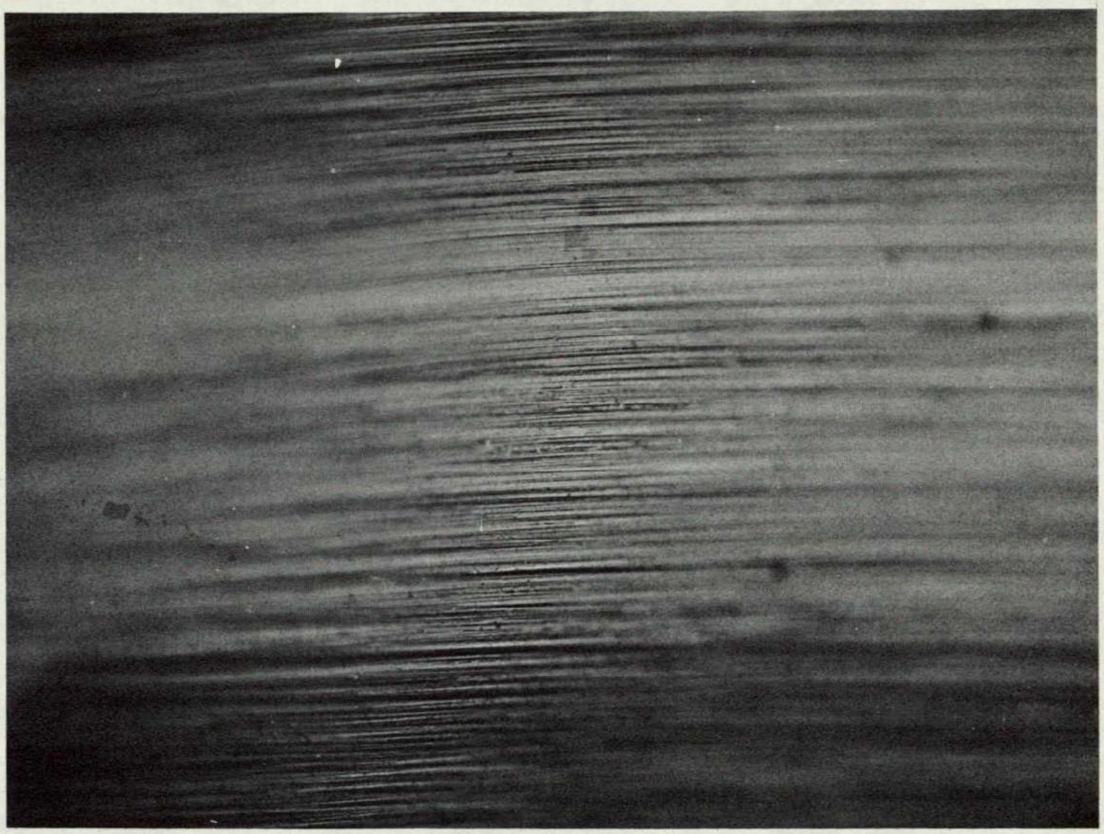
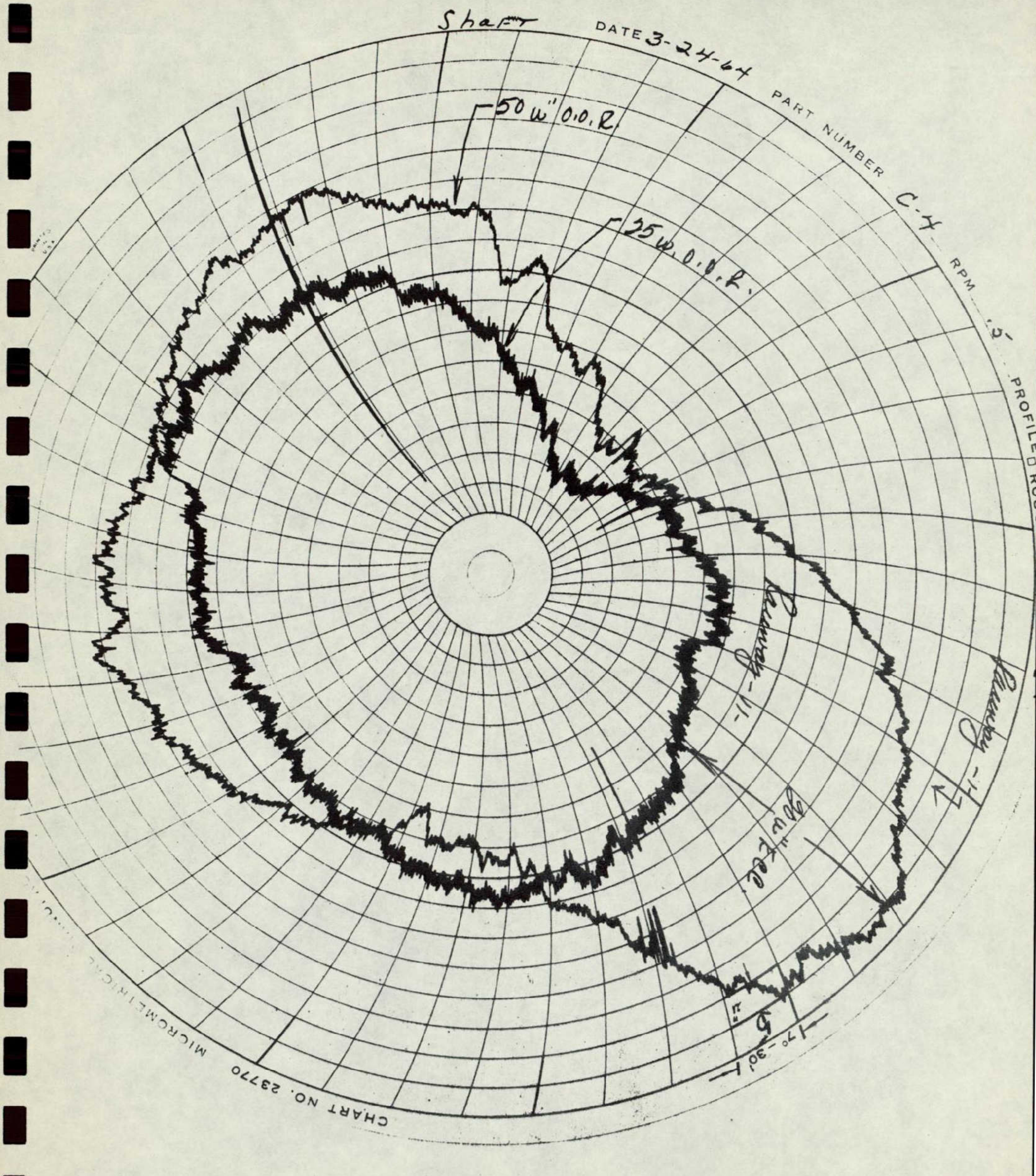


MRC C 4

Shaft #1 Side 250 X

Phase II

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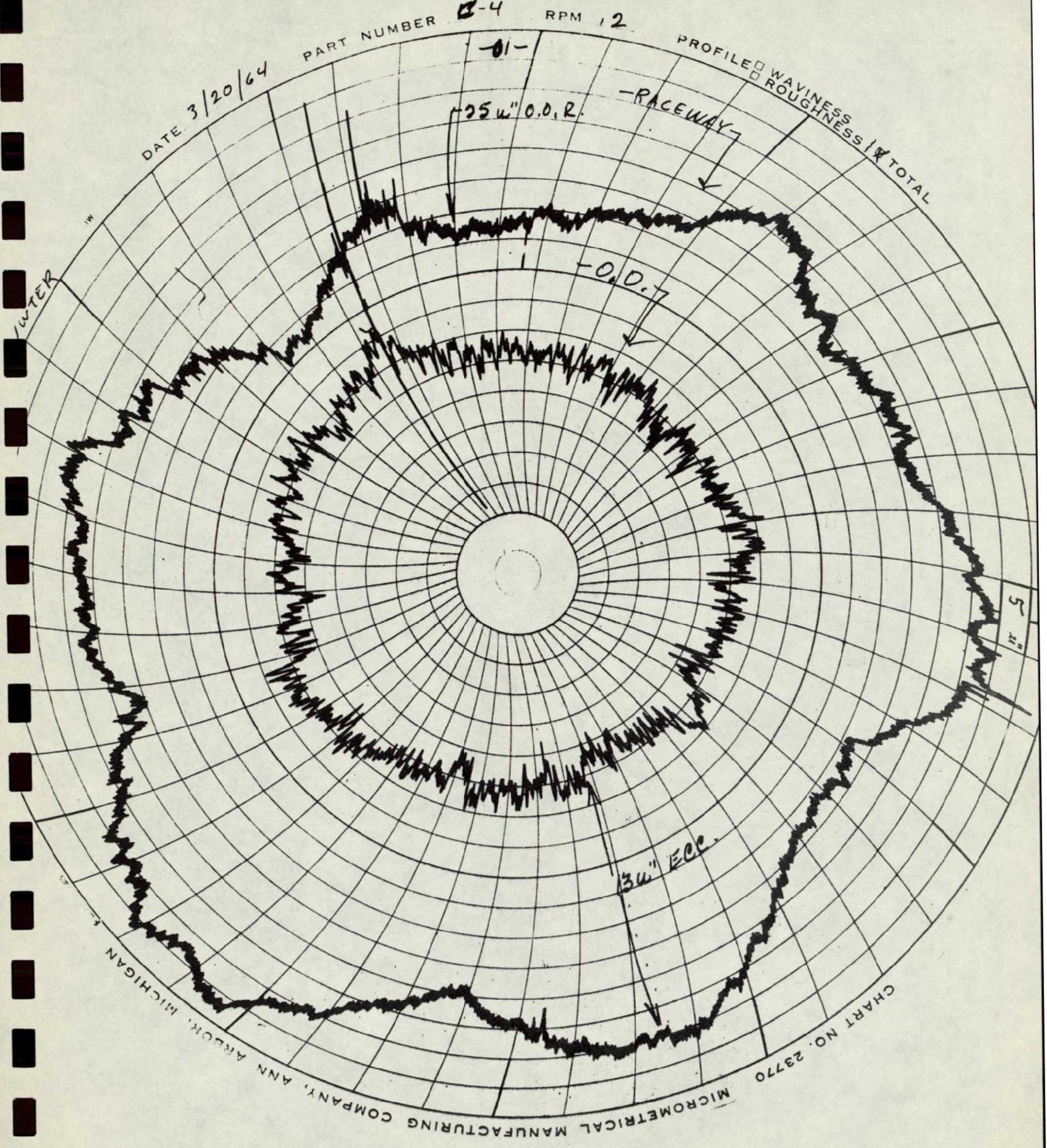
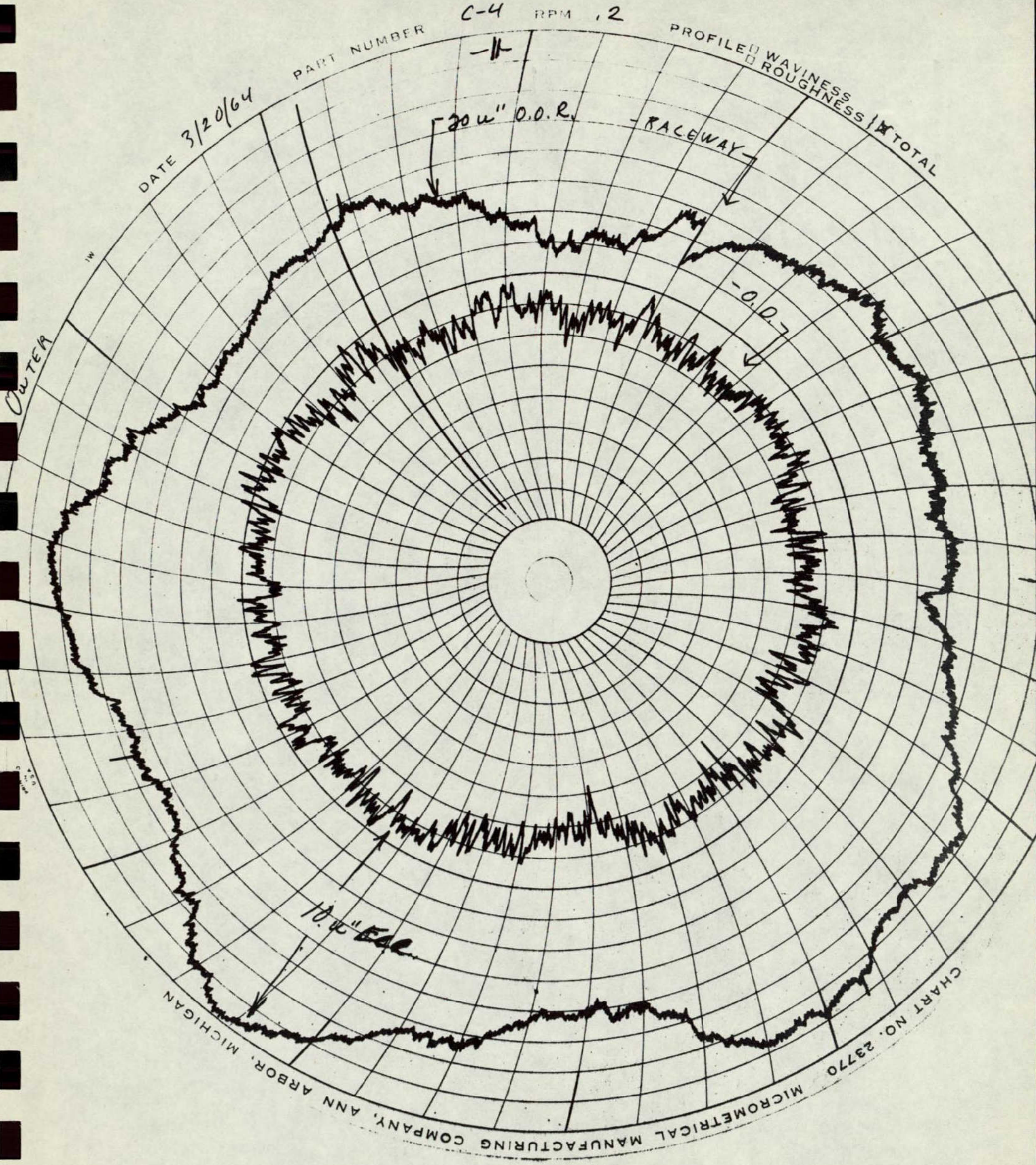
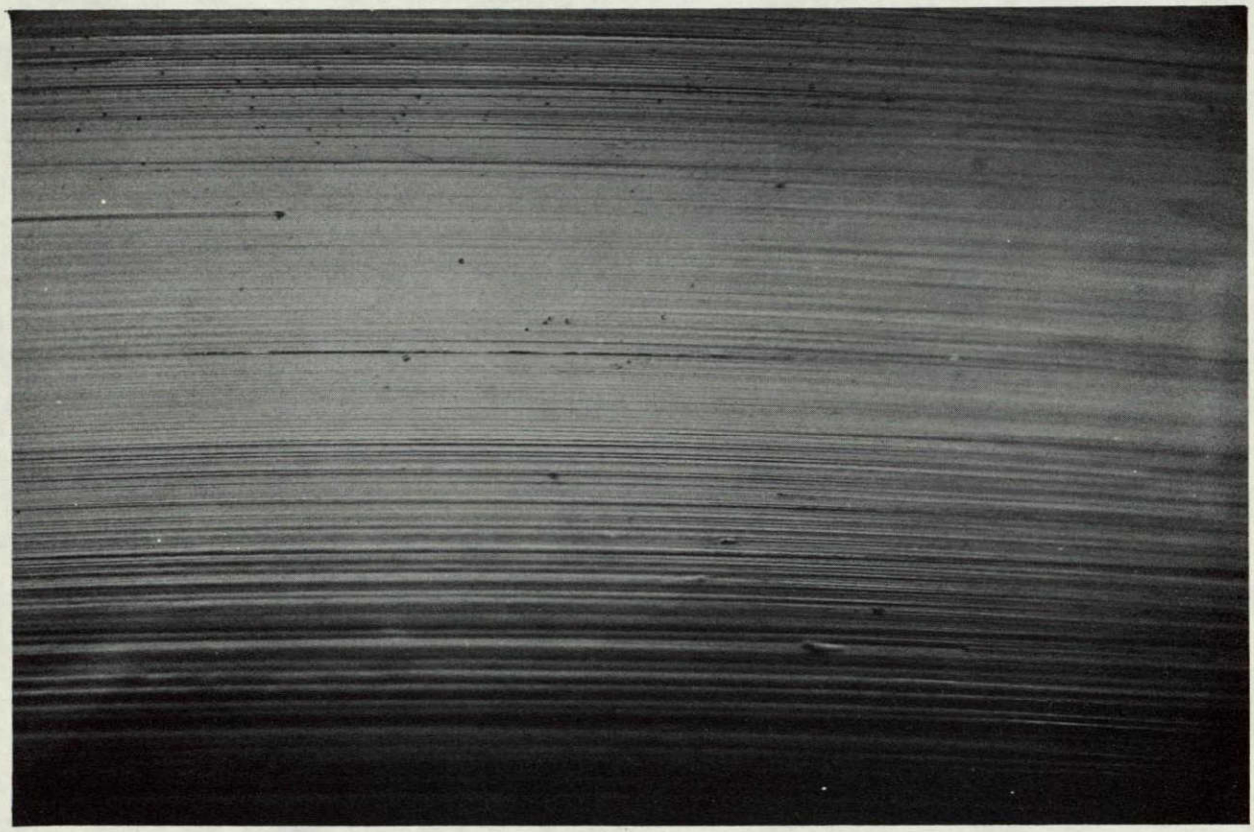


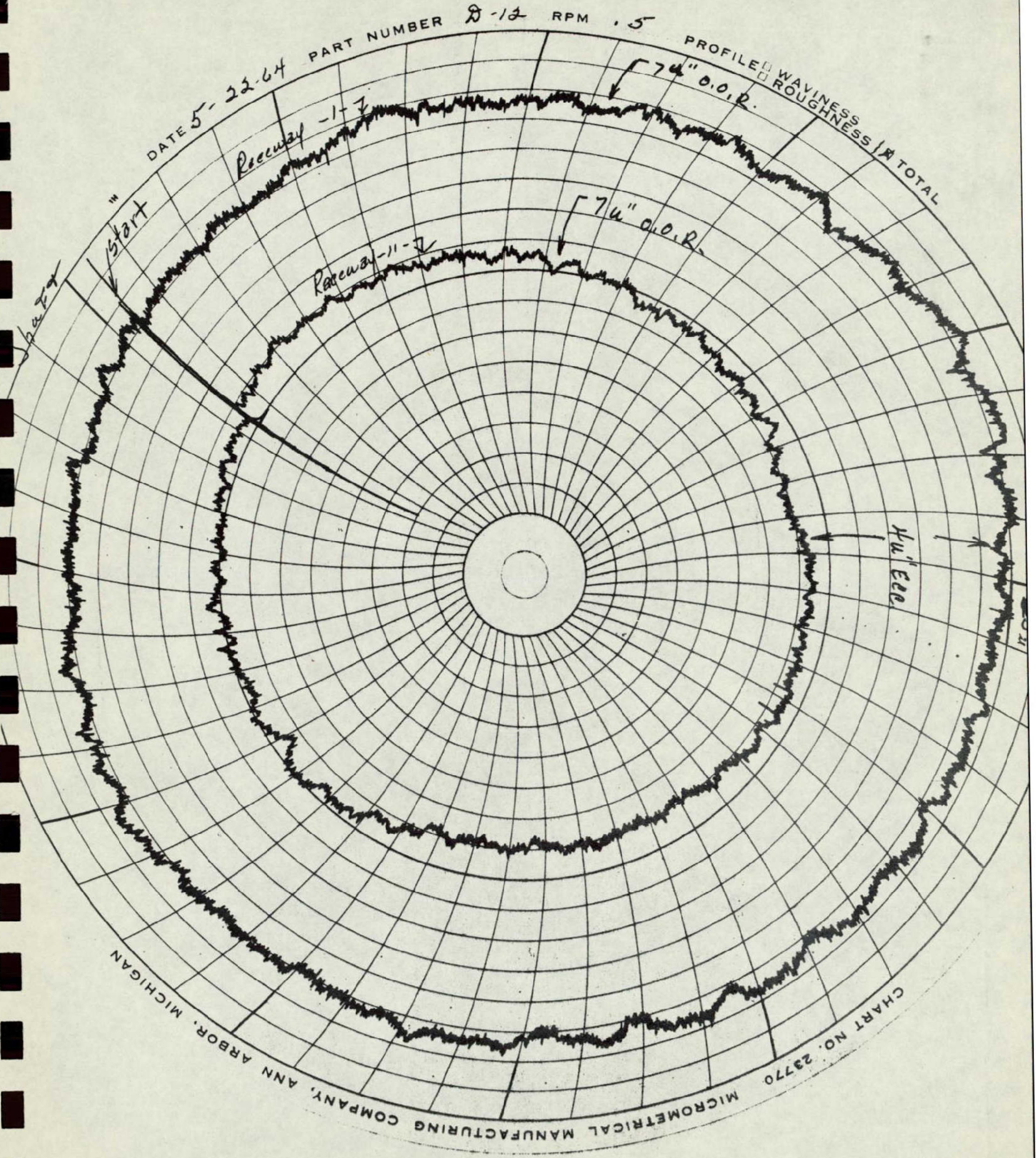

PROFICORDER TRACES OF OUTER RACE OF LOT C , BRG. 4




PROFICORDER TRACES OF OUTER RACE OF LOT C , BRG. 4



MRC D 12
Shaft #1 Side 250 X
Phase II

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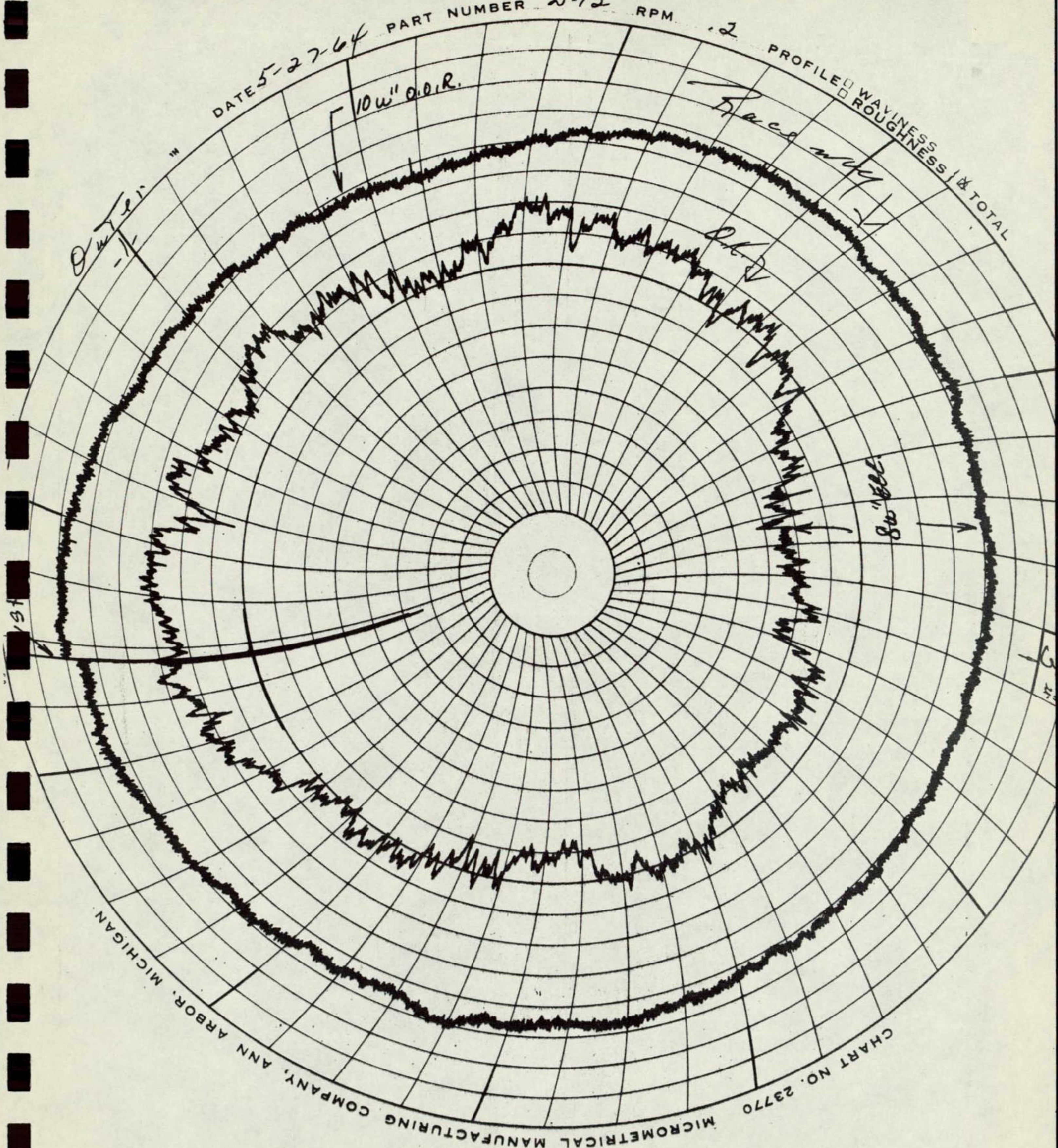


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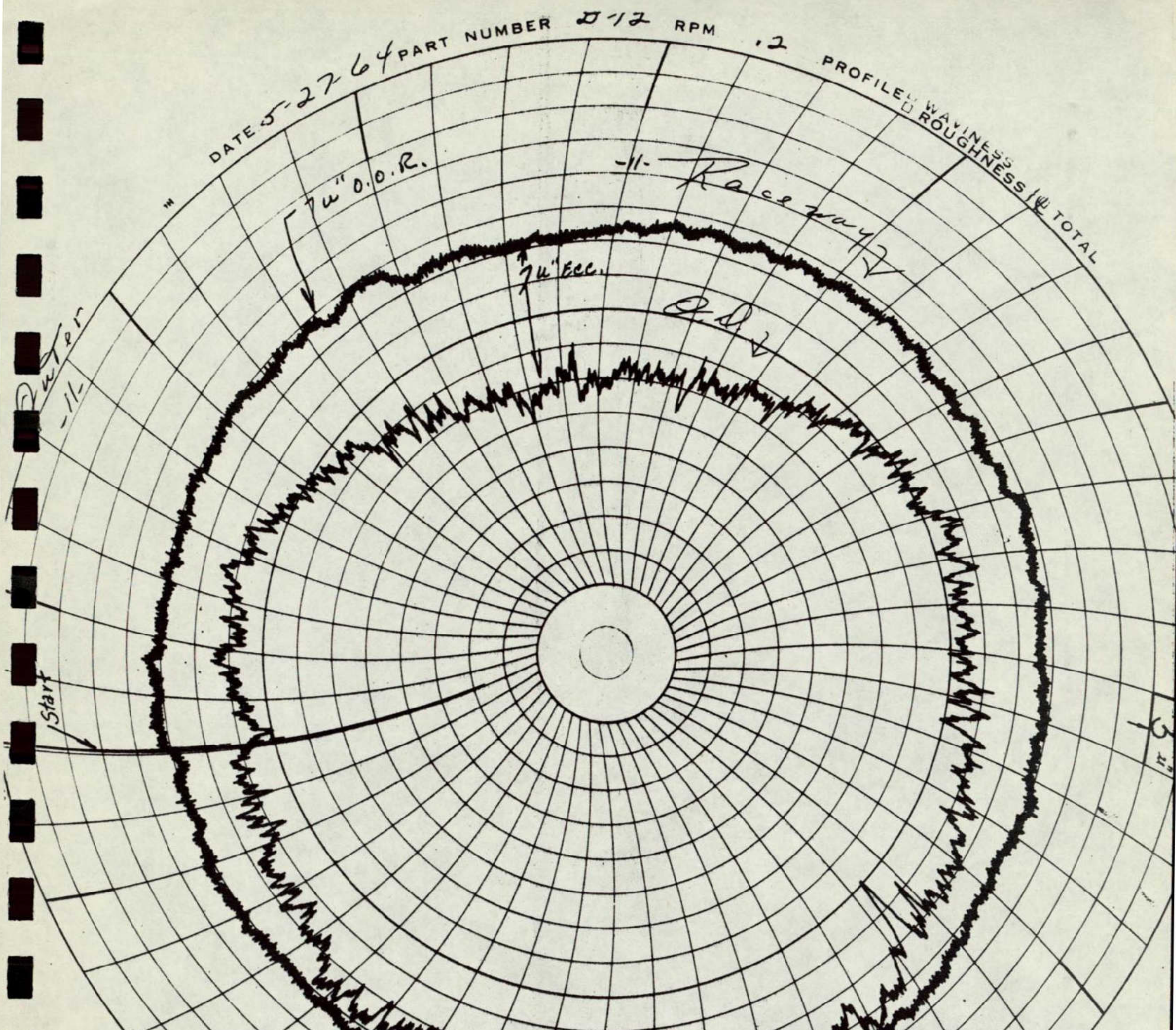


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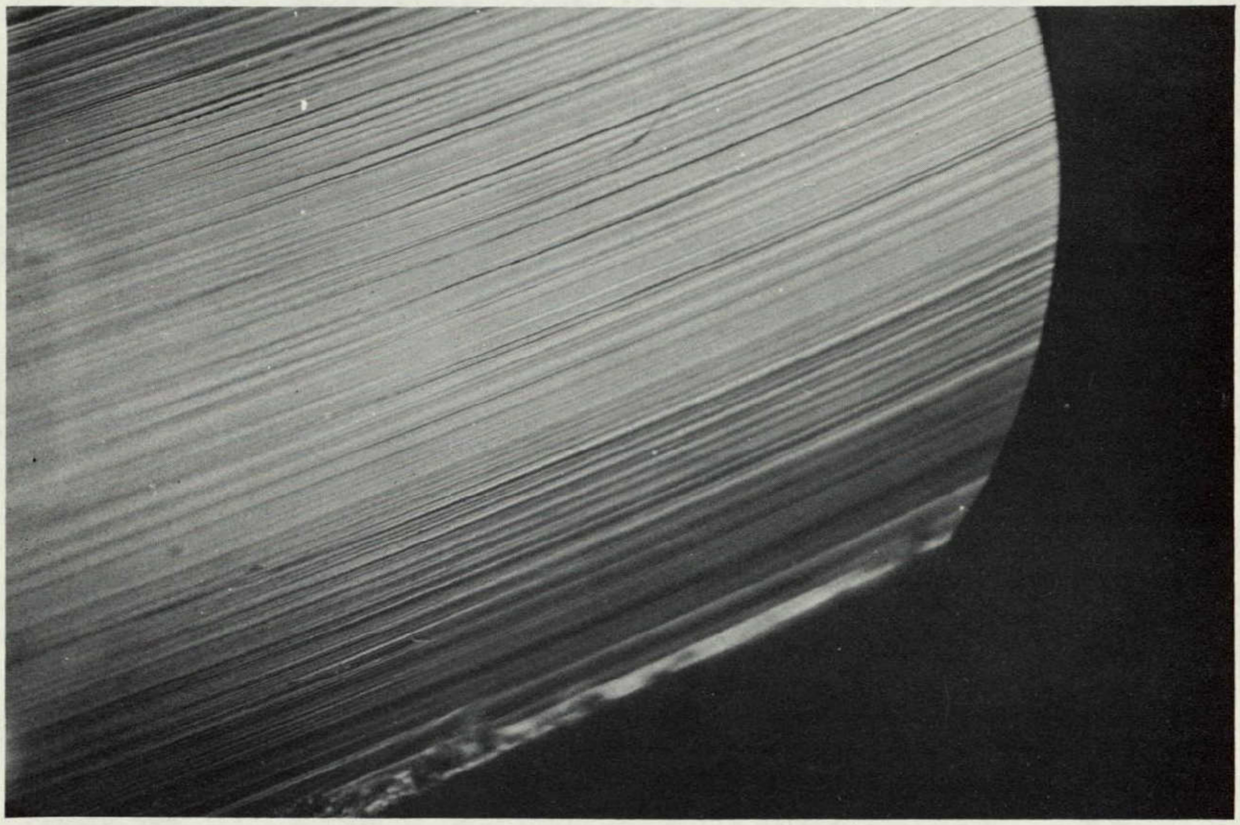
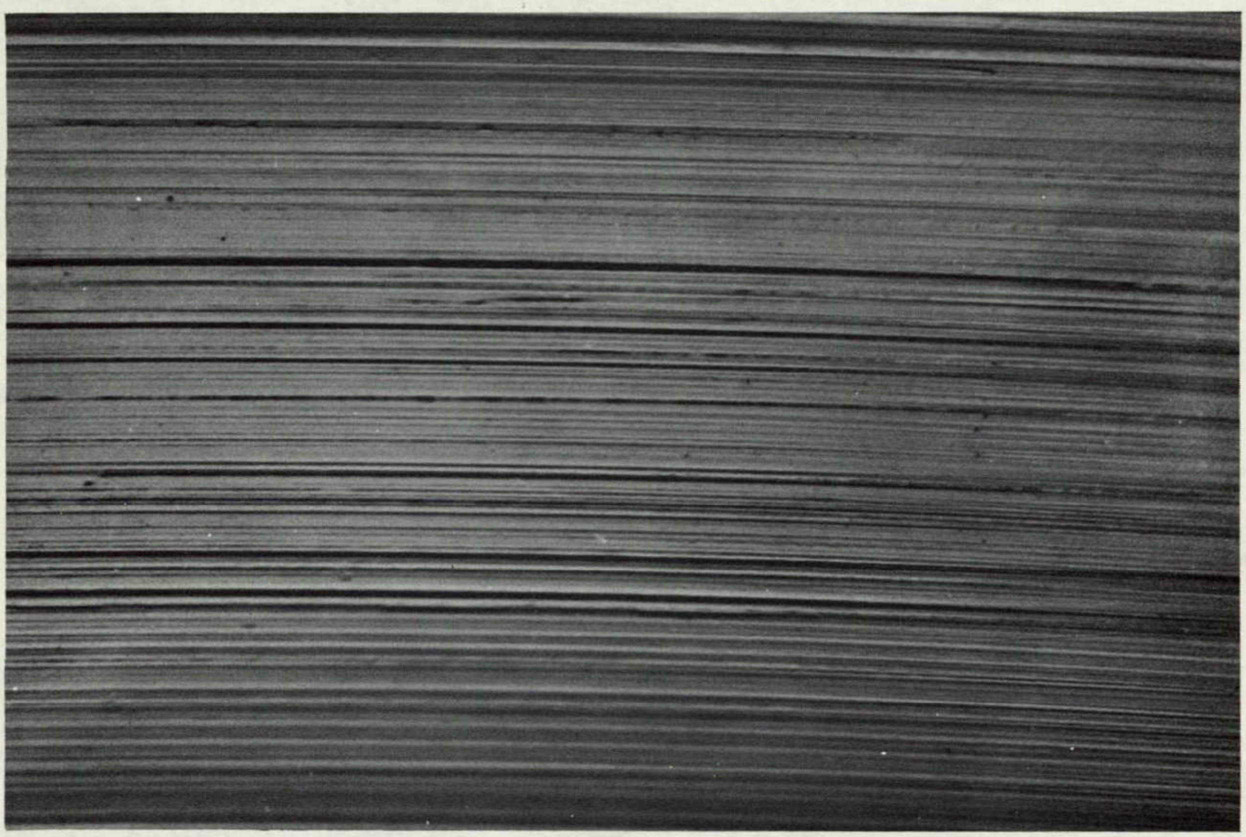
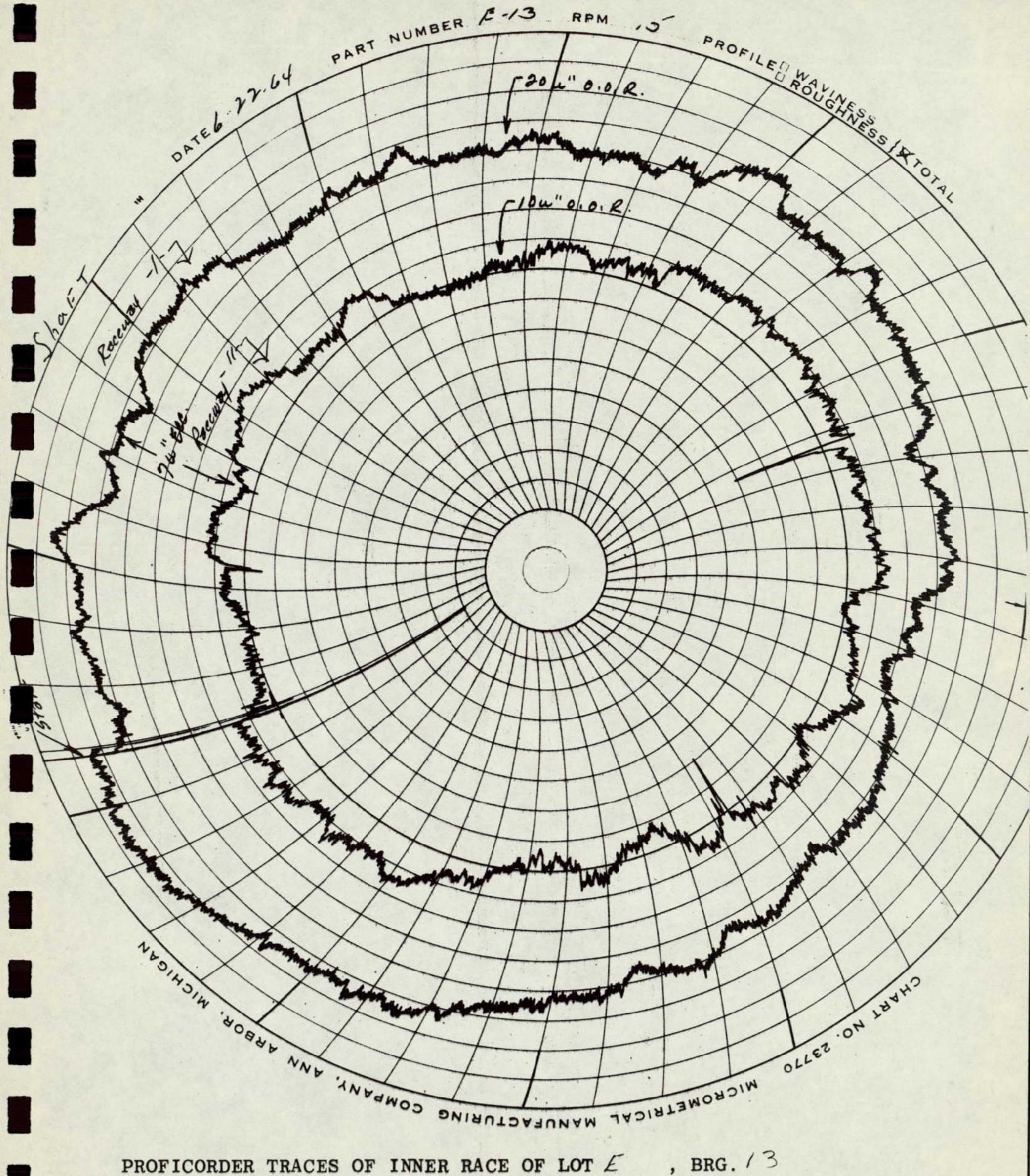


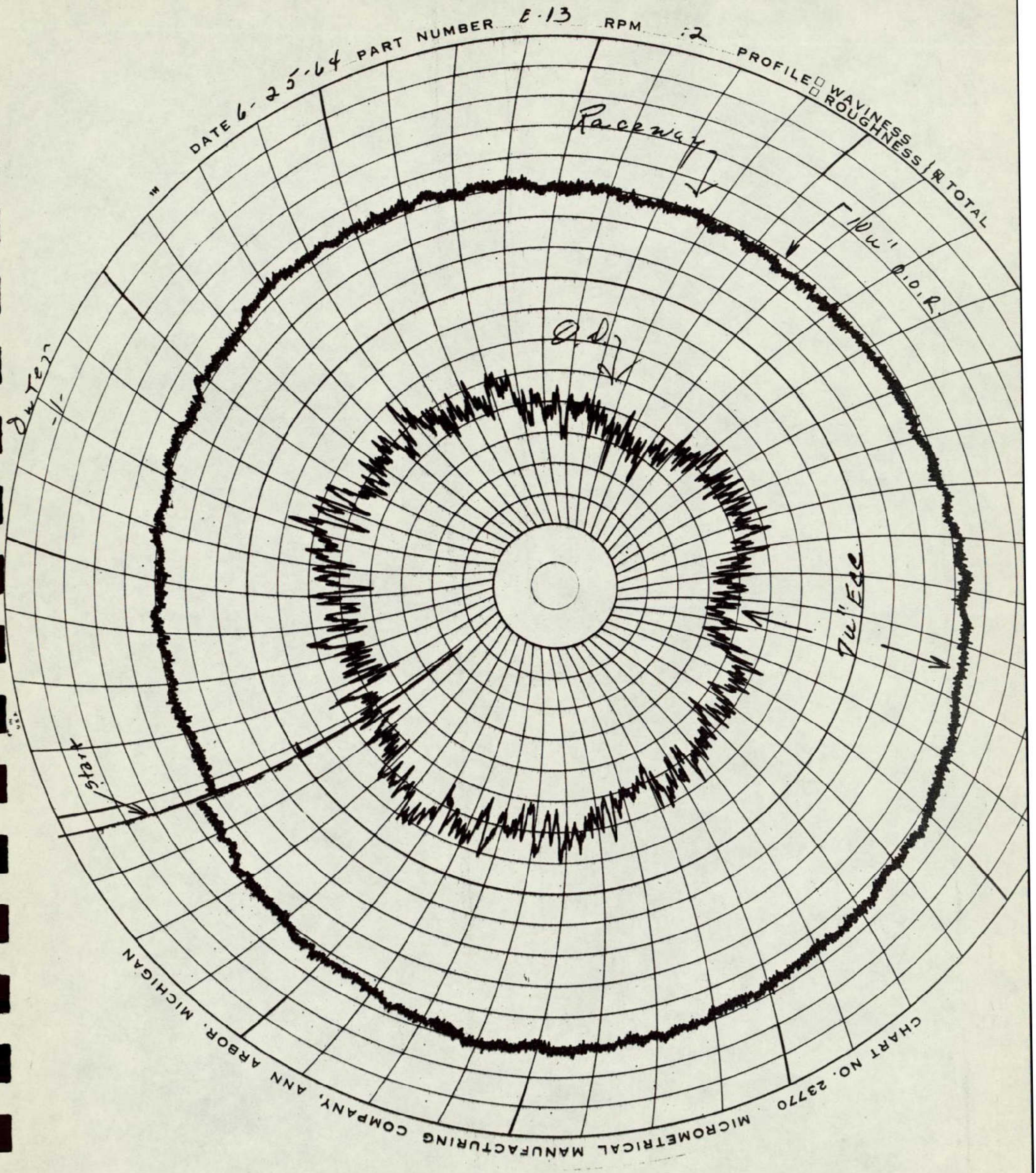
MRC E 13
Shaft #2 Side 250 X
Phase II



MRC E 13
Shaft #1 Side 500 X
Phase II




PROFICORDER TRACES OF INNER RACE OF LOT E , BRG. 13

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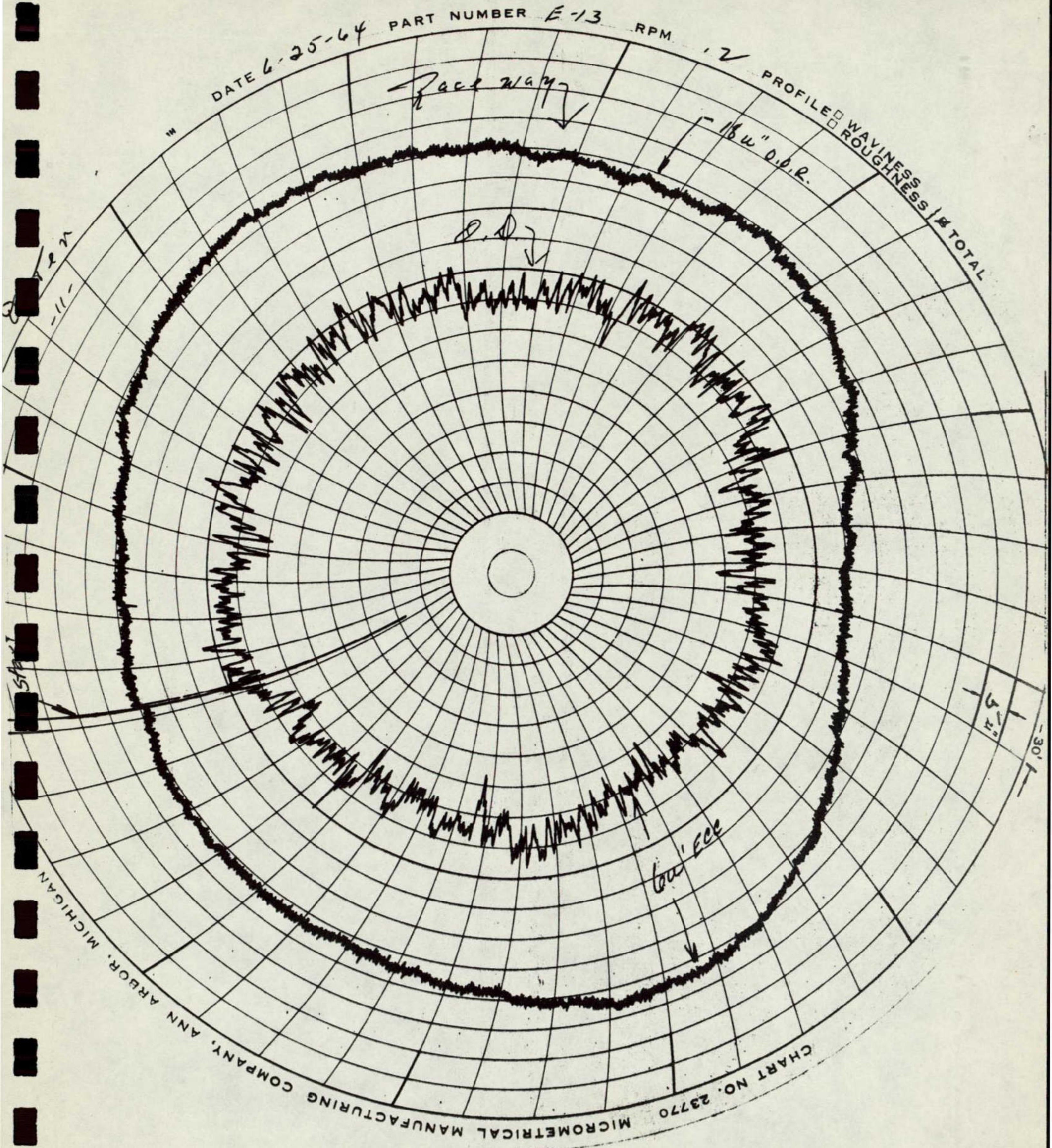
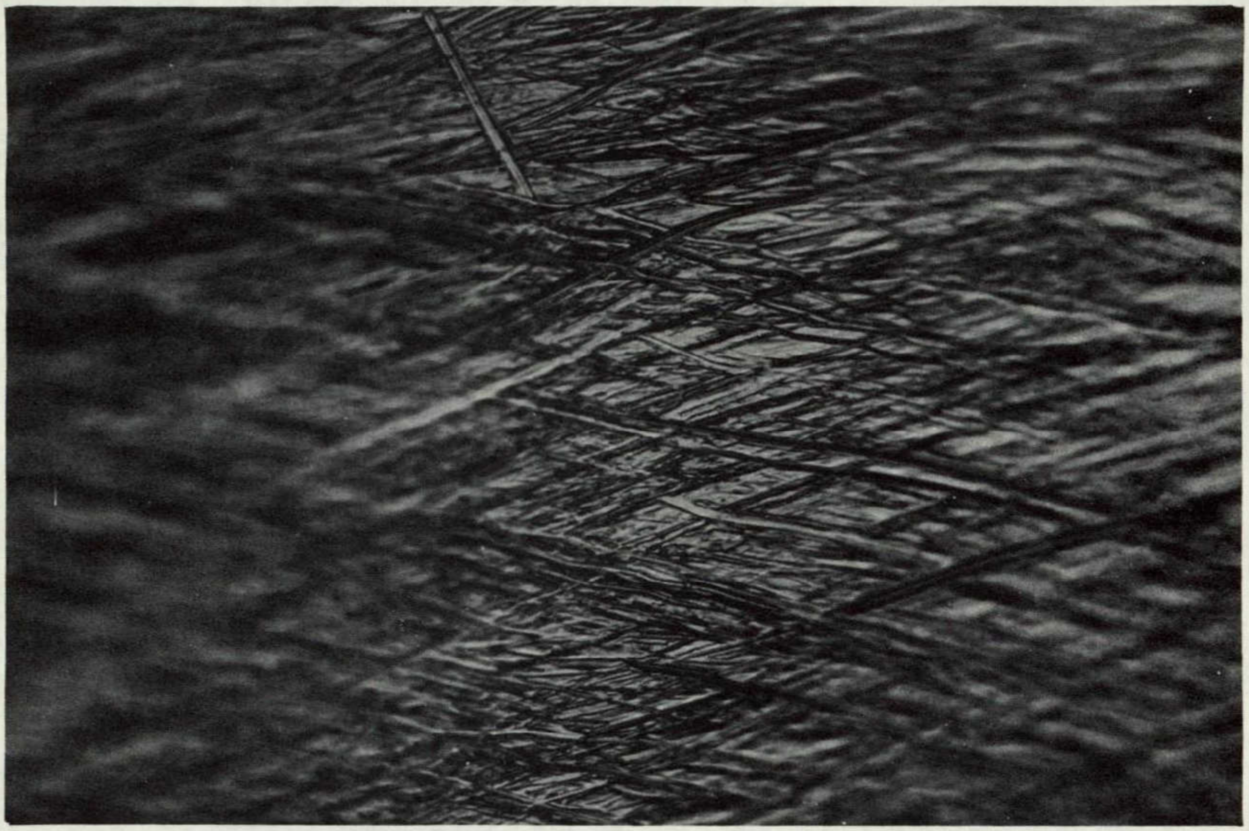



PROFICORDER TRACES OF OUTER RACE OF LOT E , BRG. 13

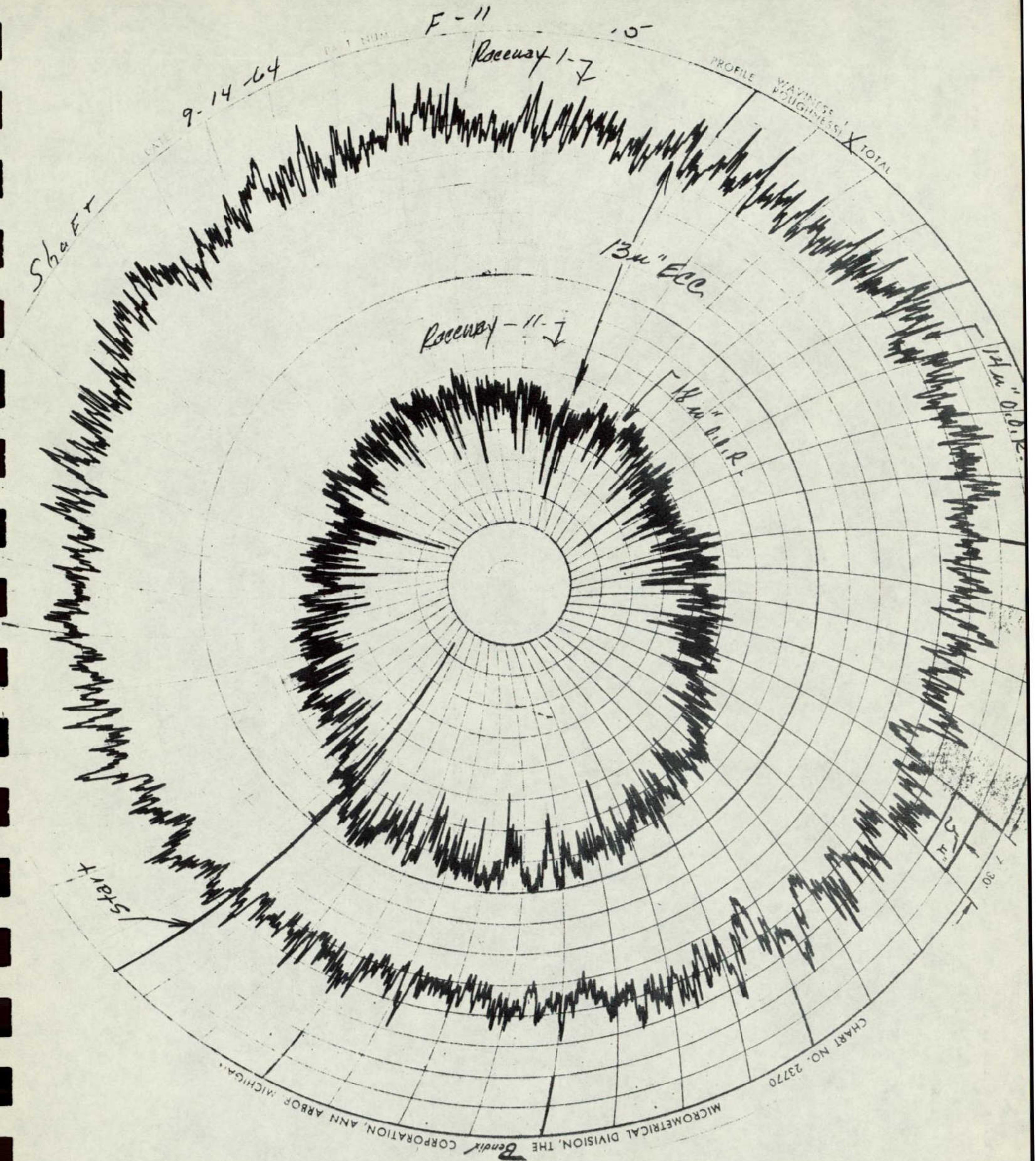
MRC F 11

Shaft #1 Side 250 X

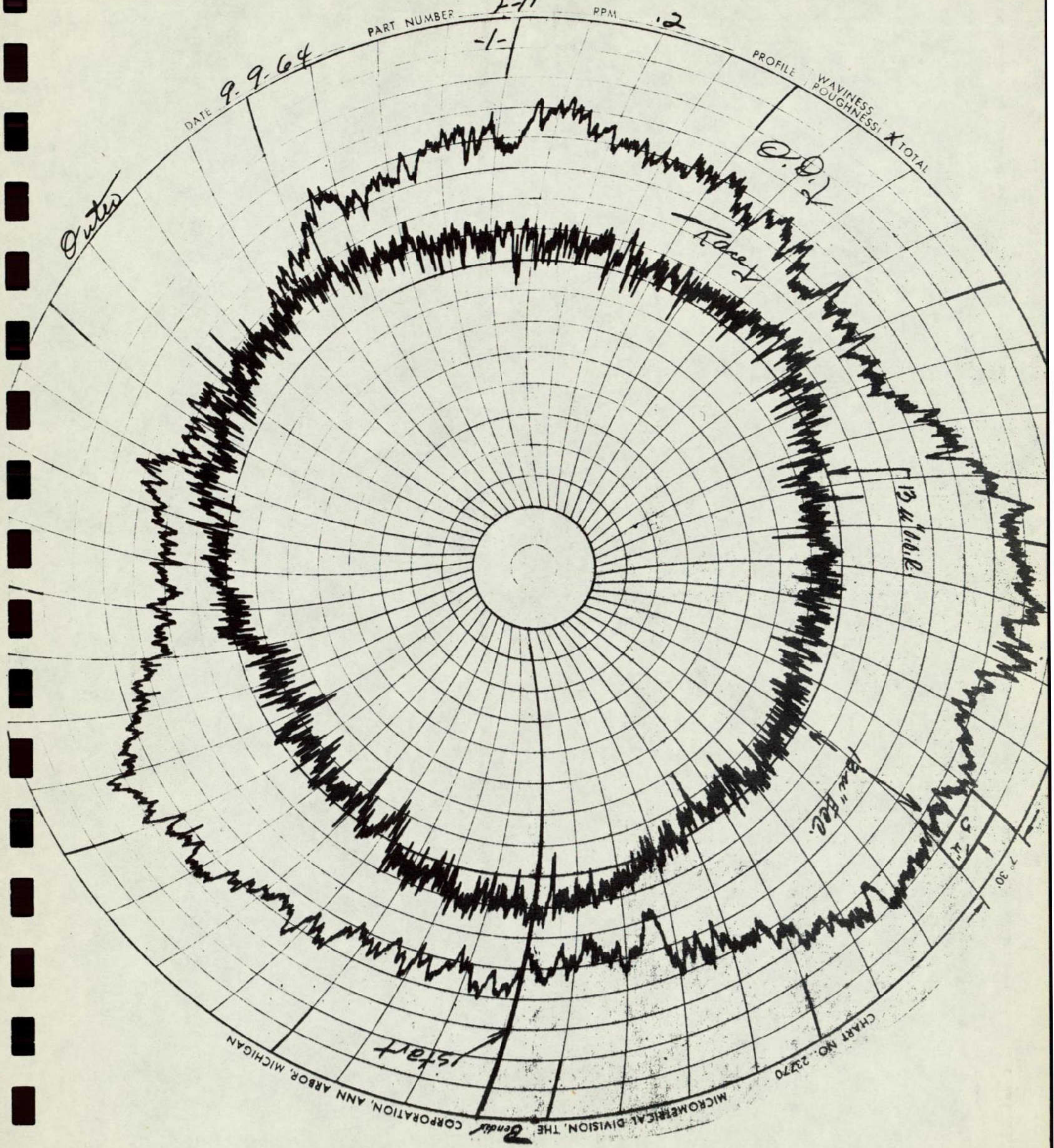
Phase II



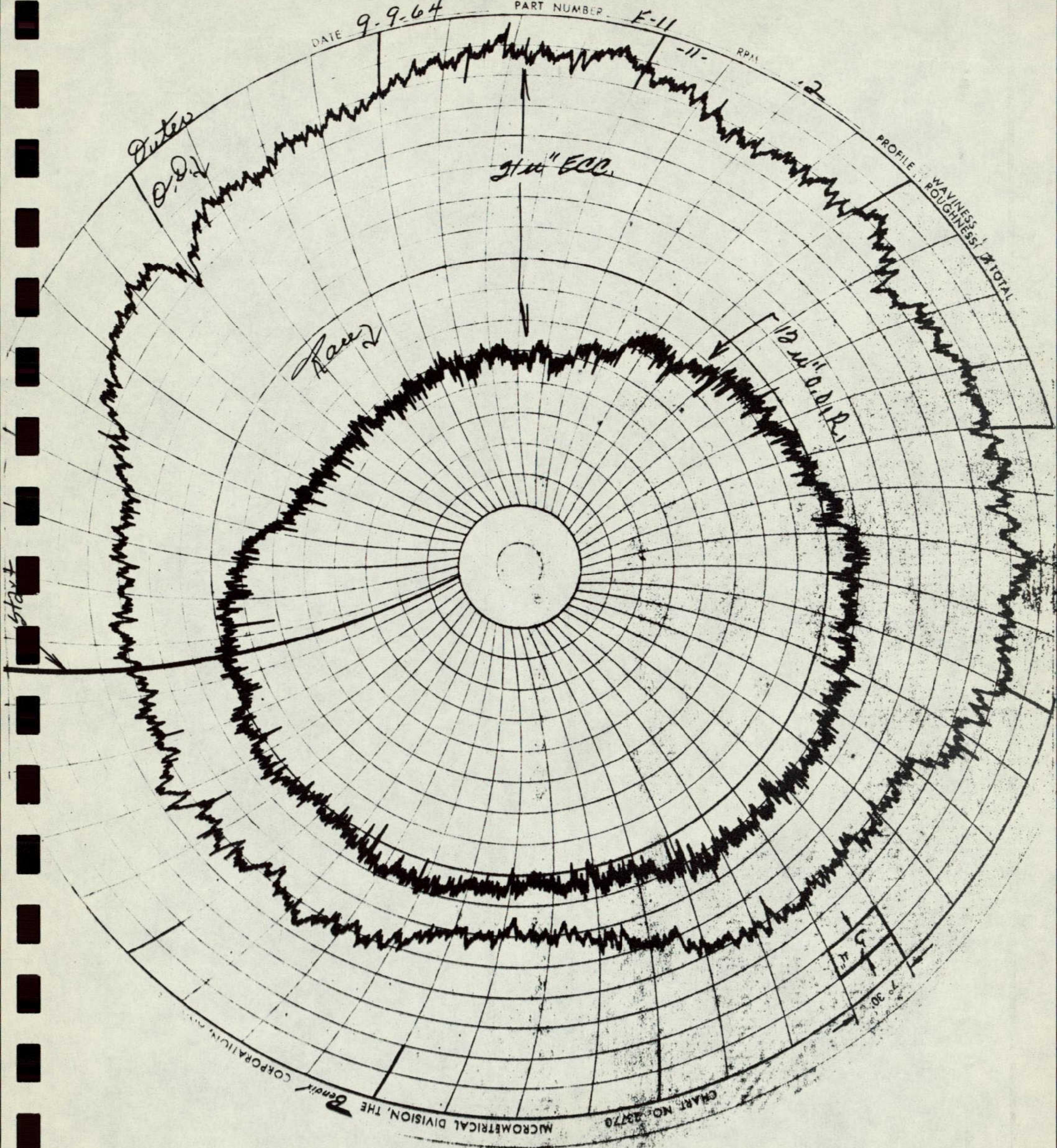
MRC F 11
Shaft #2 Side 500 X
Phase II




PROFICORDER TRACES OF INNER RACE OF LOT F , BRG. 11




PROFICORDER TRACES OF OUTER RACE OF LOT F , BRG. 11

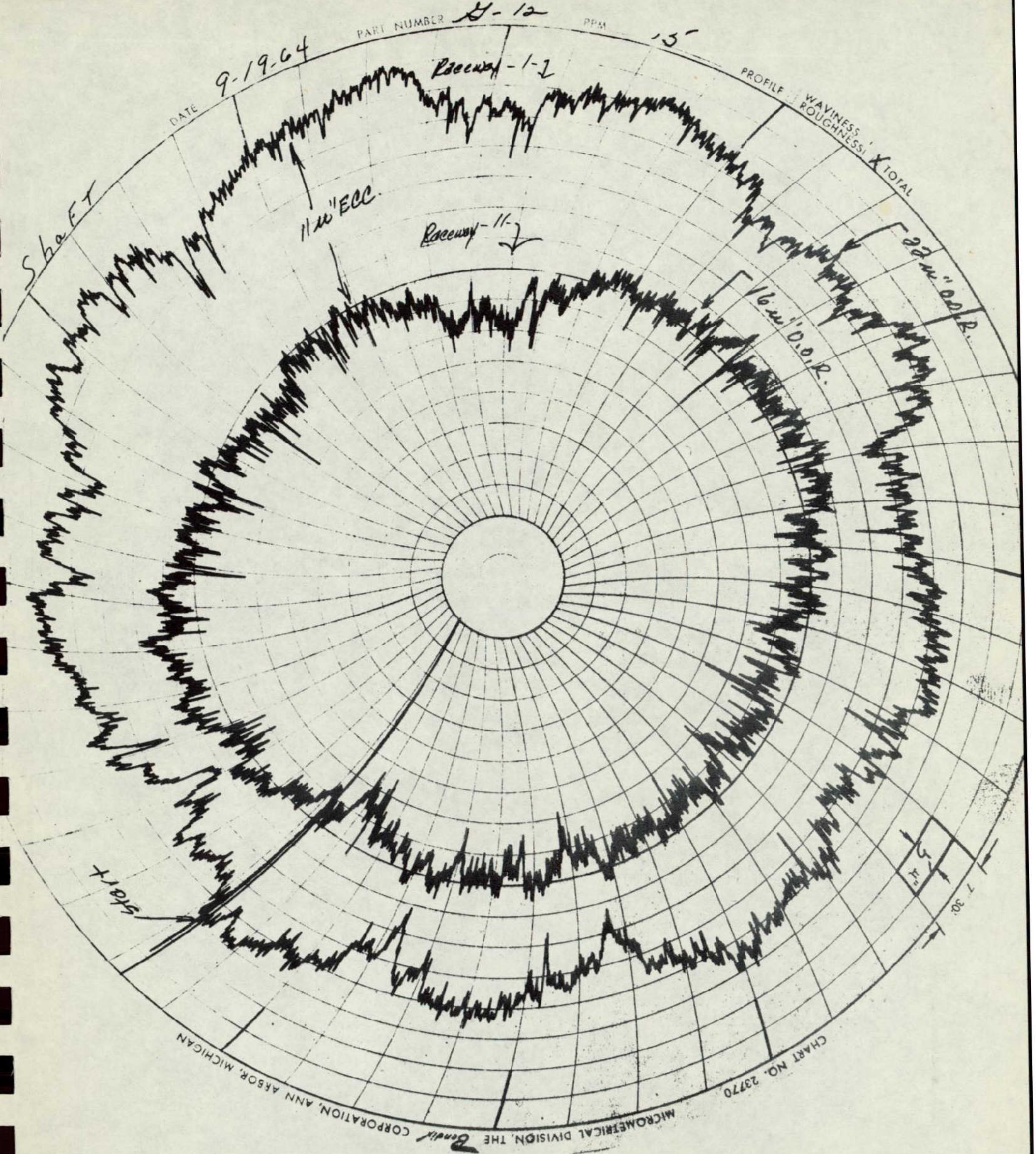



PROFICORDER TRACES OF OUTER RACE OF LOT F , BRG. 11

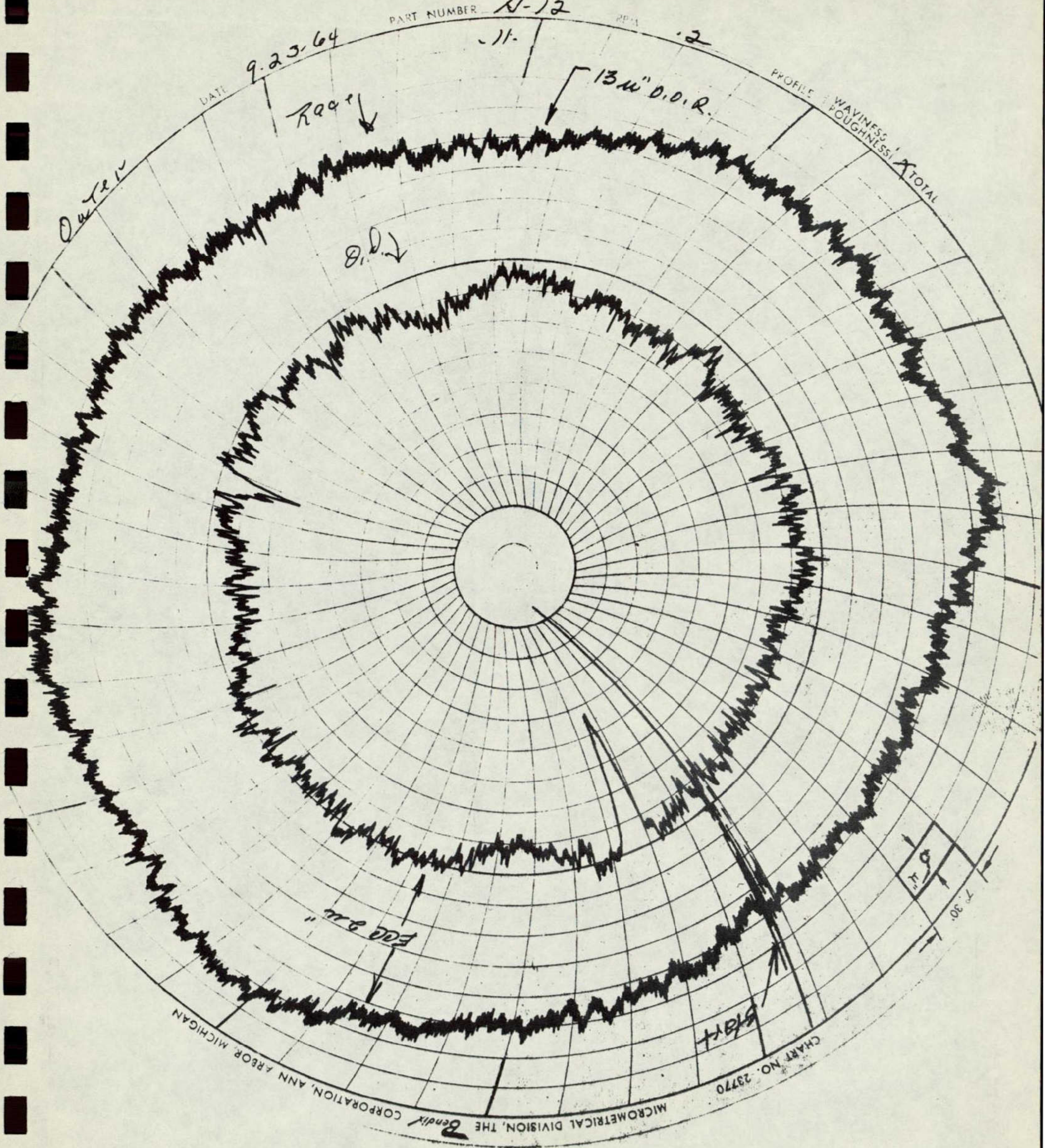
MRC G 12

Shaft #2 Side 250 X

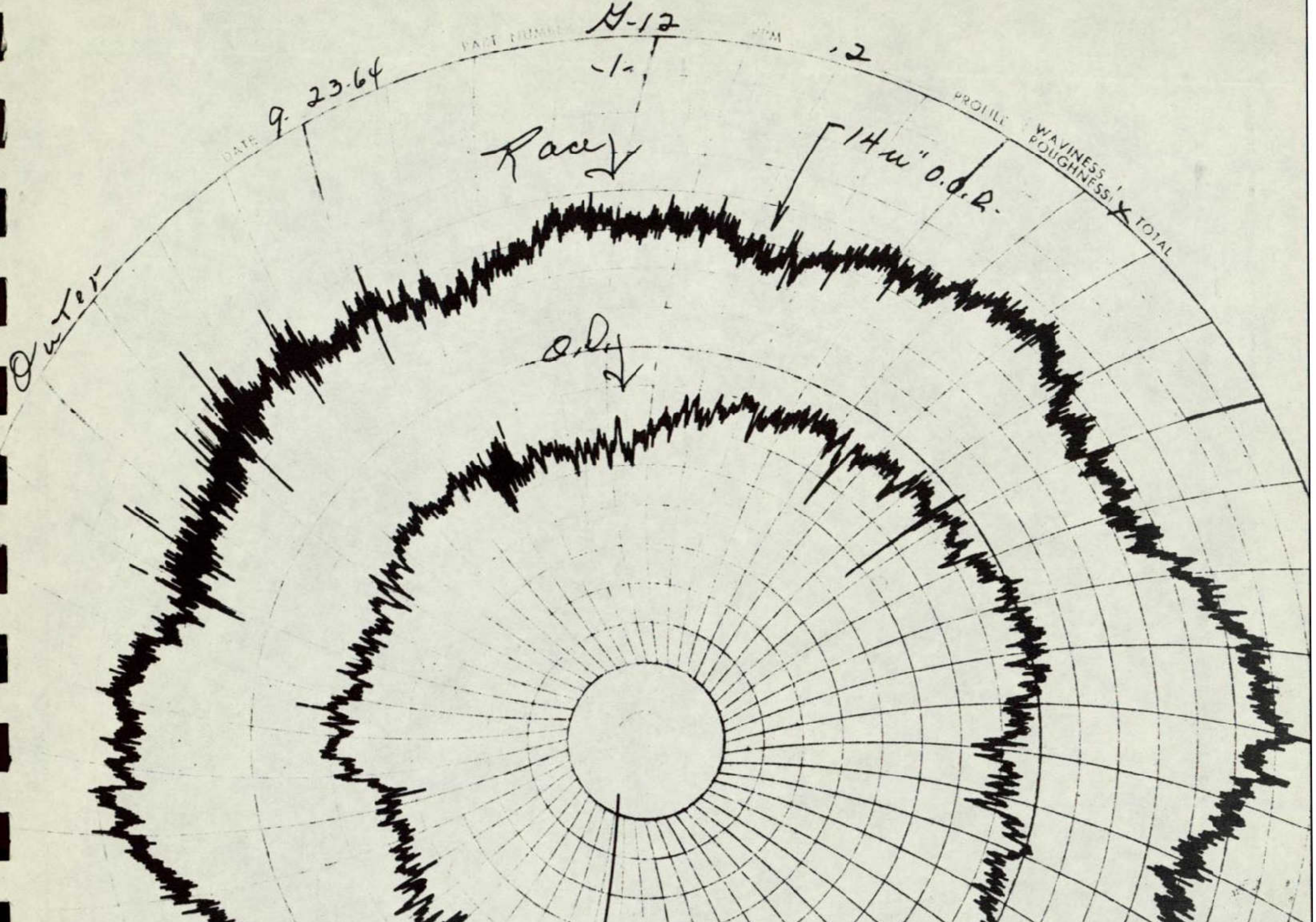
Phase II




PROFICORDER TRACES OF INNER RACE OF LOT G , BRG. 12




PROFICORDER TRACES OF OUTER RACE OF LOT G , BRG. 12

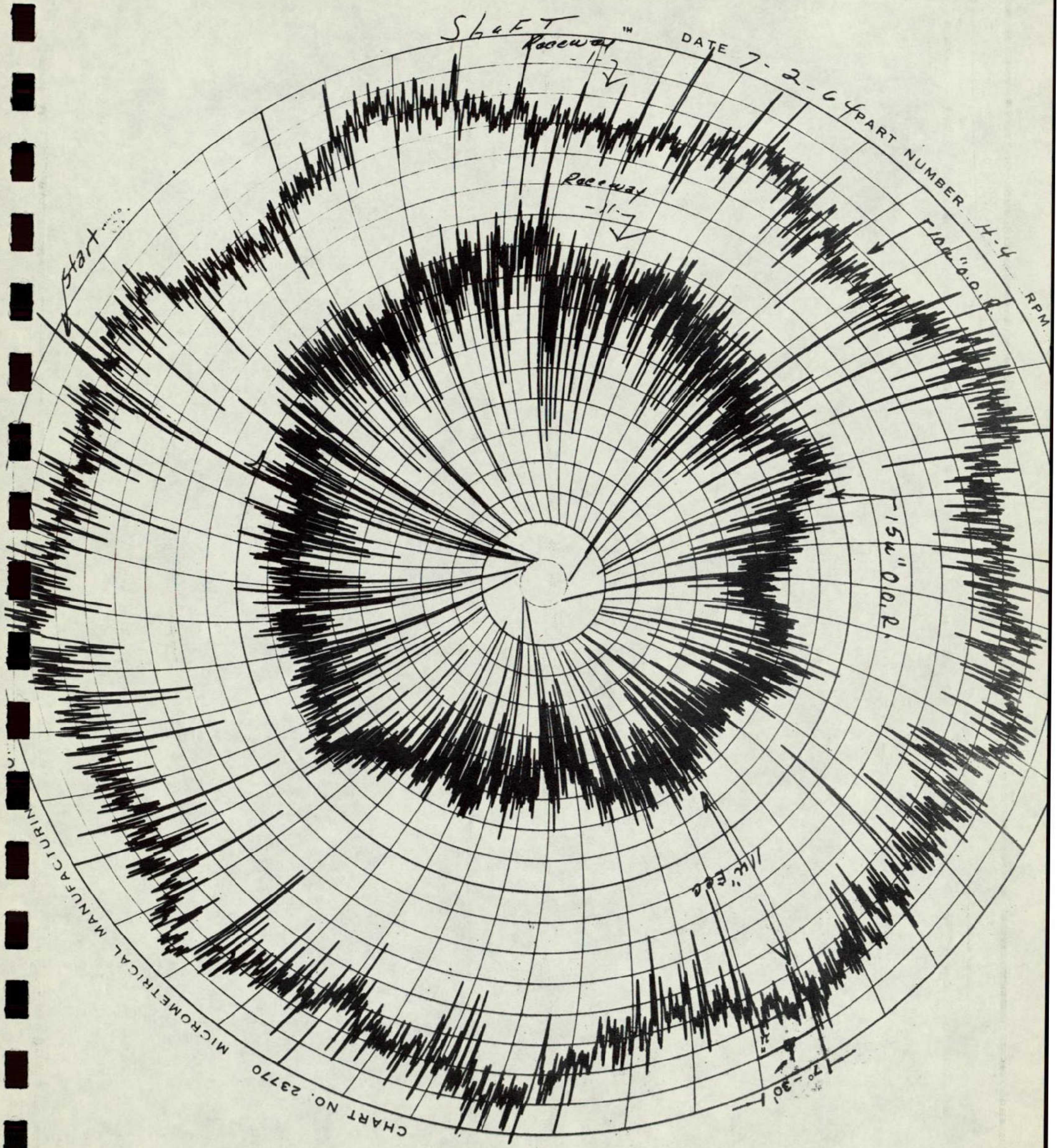



PROFICORDER TRACES OF OUTER RACE OF LOT G , BRG. 12

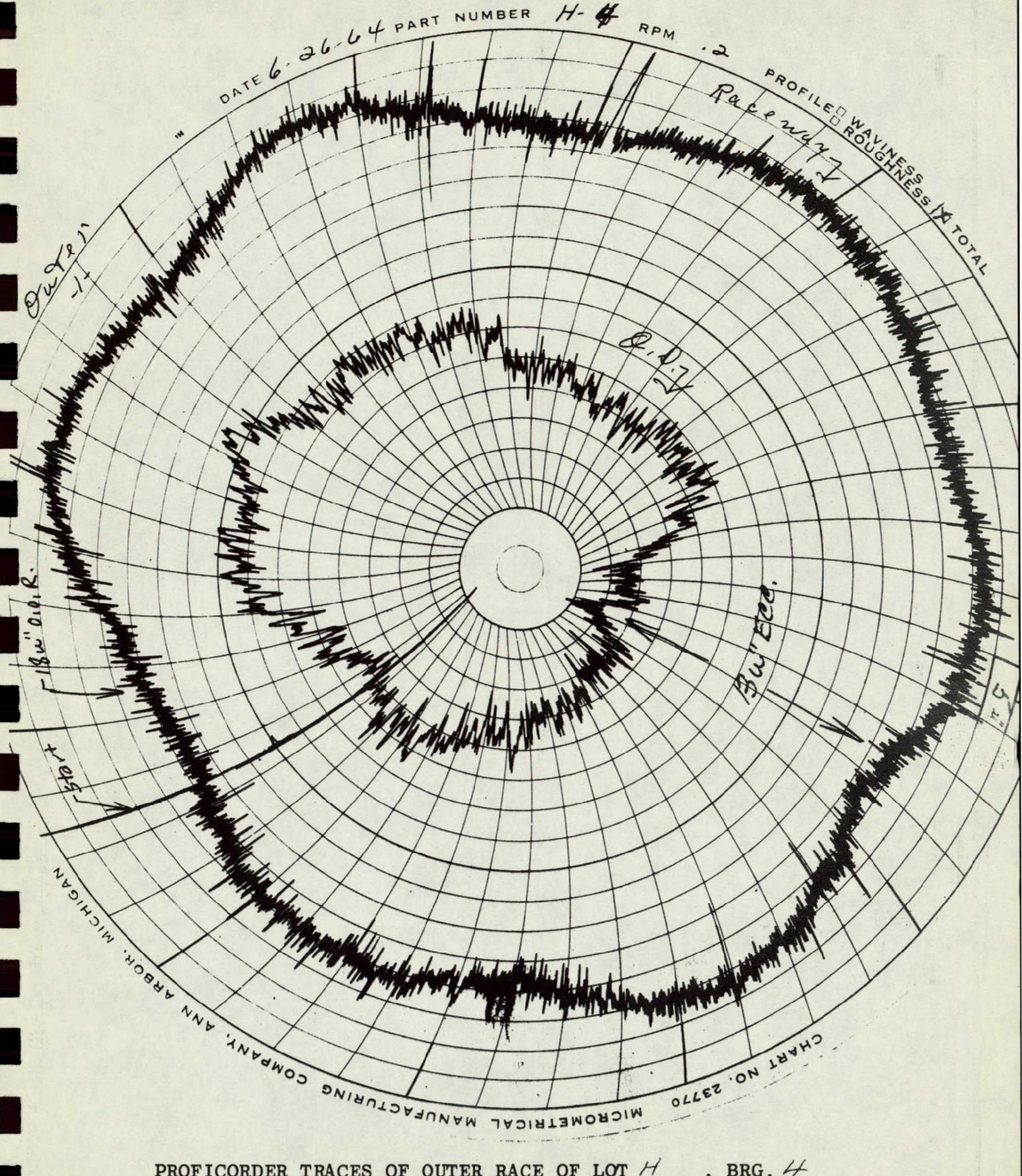
MRC H 4

Shaft #2 Side 250 X

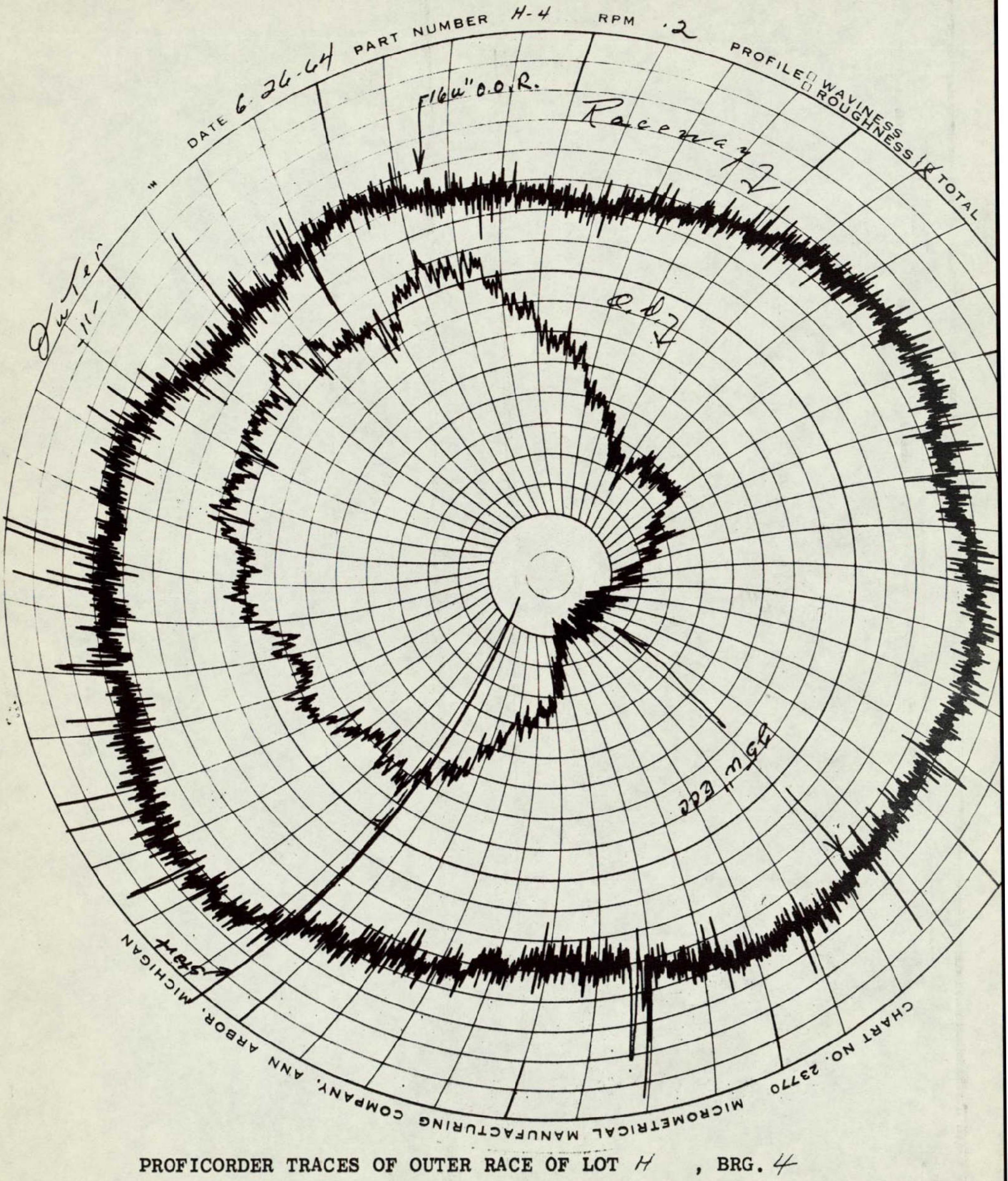
Phase II



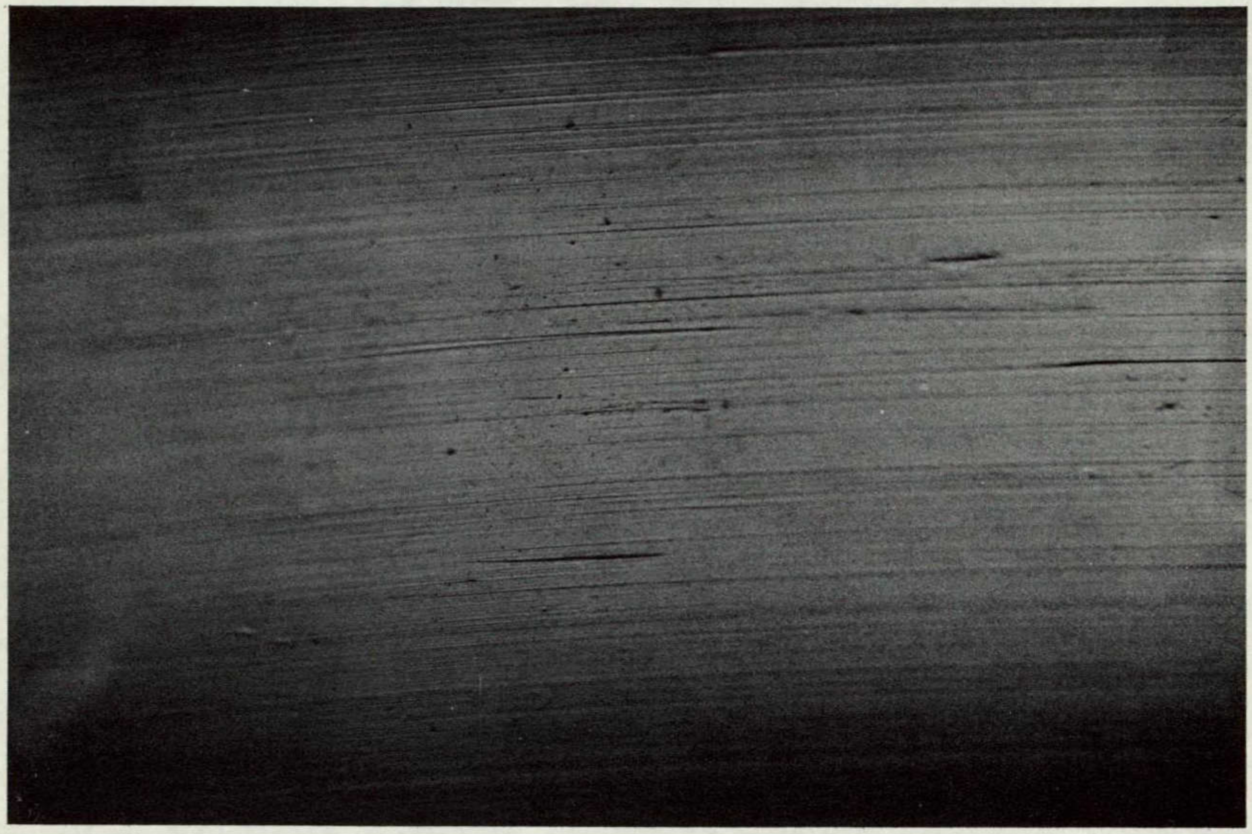

PROFICORDER TRACES OF INNER RACE OF LOT *H* , BRG. *4*




PROFICORDER TRACES OF OUTER RACE OF LOT H , BRG. 4




PROFICORDER TRACES OF OUTER RACE OF LOT H , BRG. 4



MRC I 1

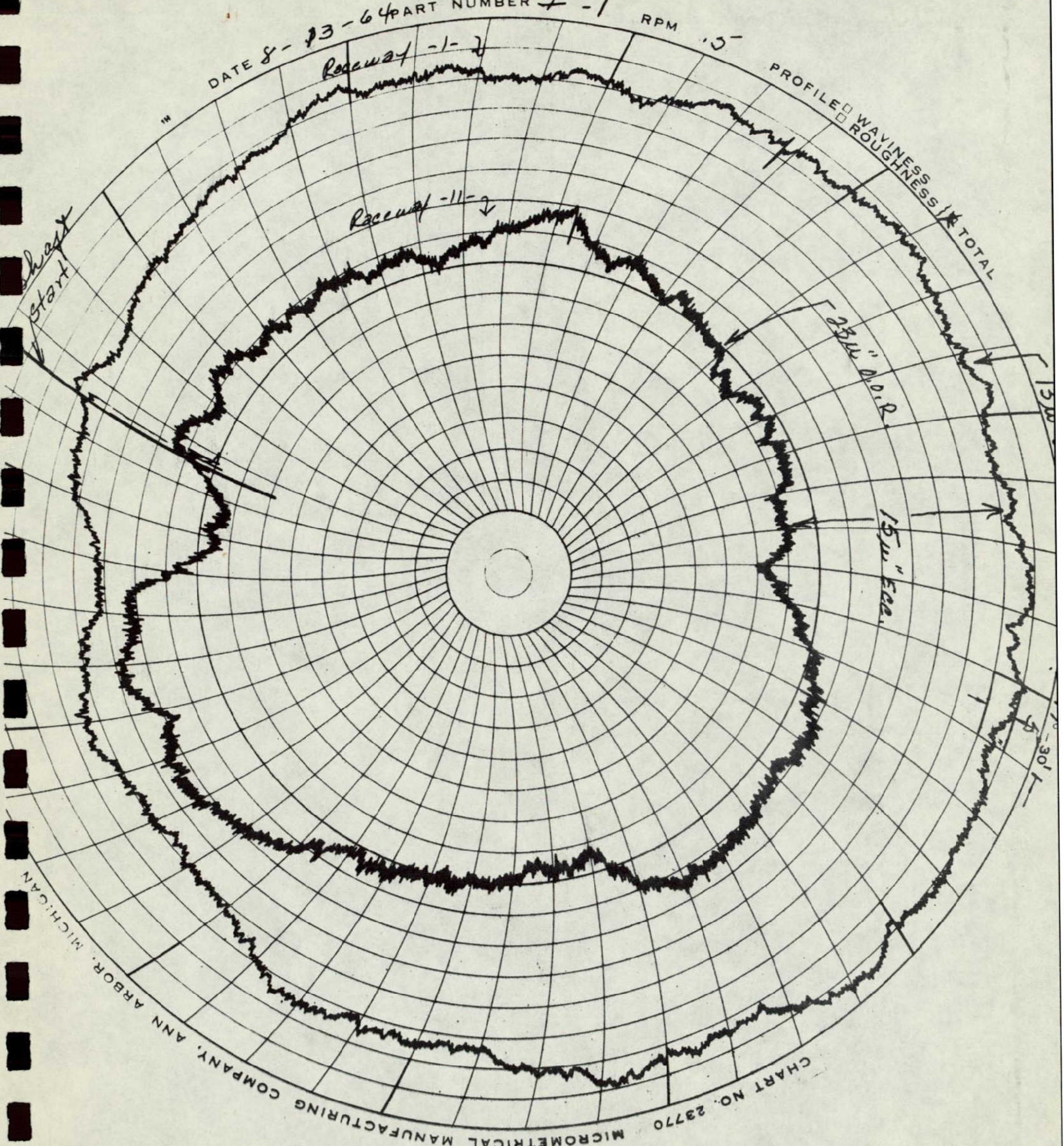
Shaft #2 Side 250 X

Phase II

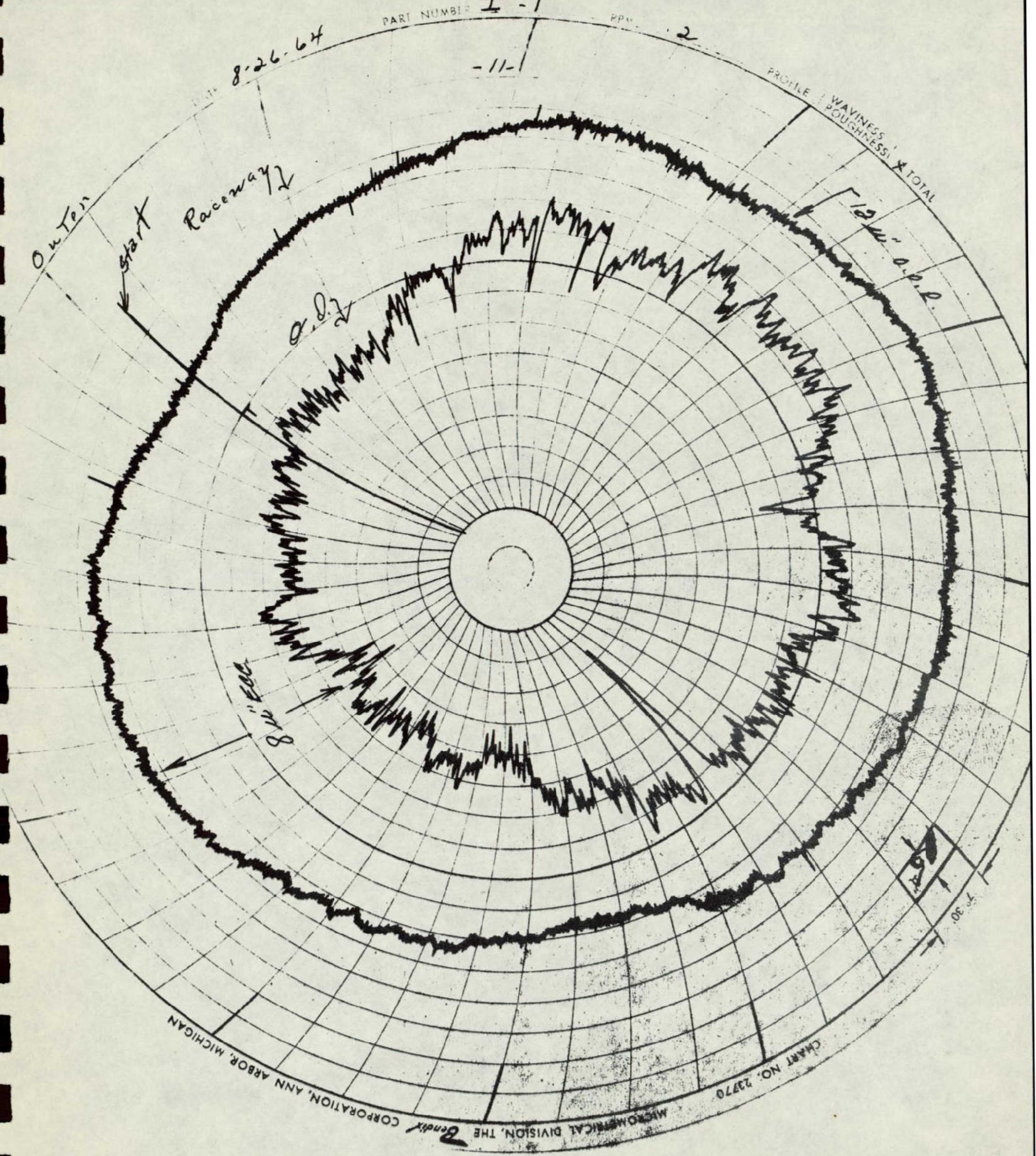
MRC I 1

Shaft #2 Side 500 X

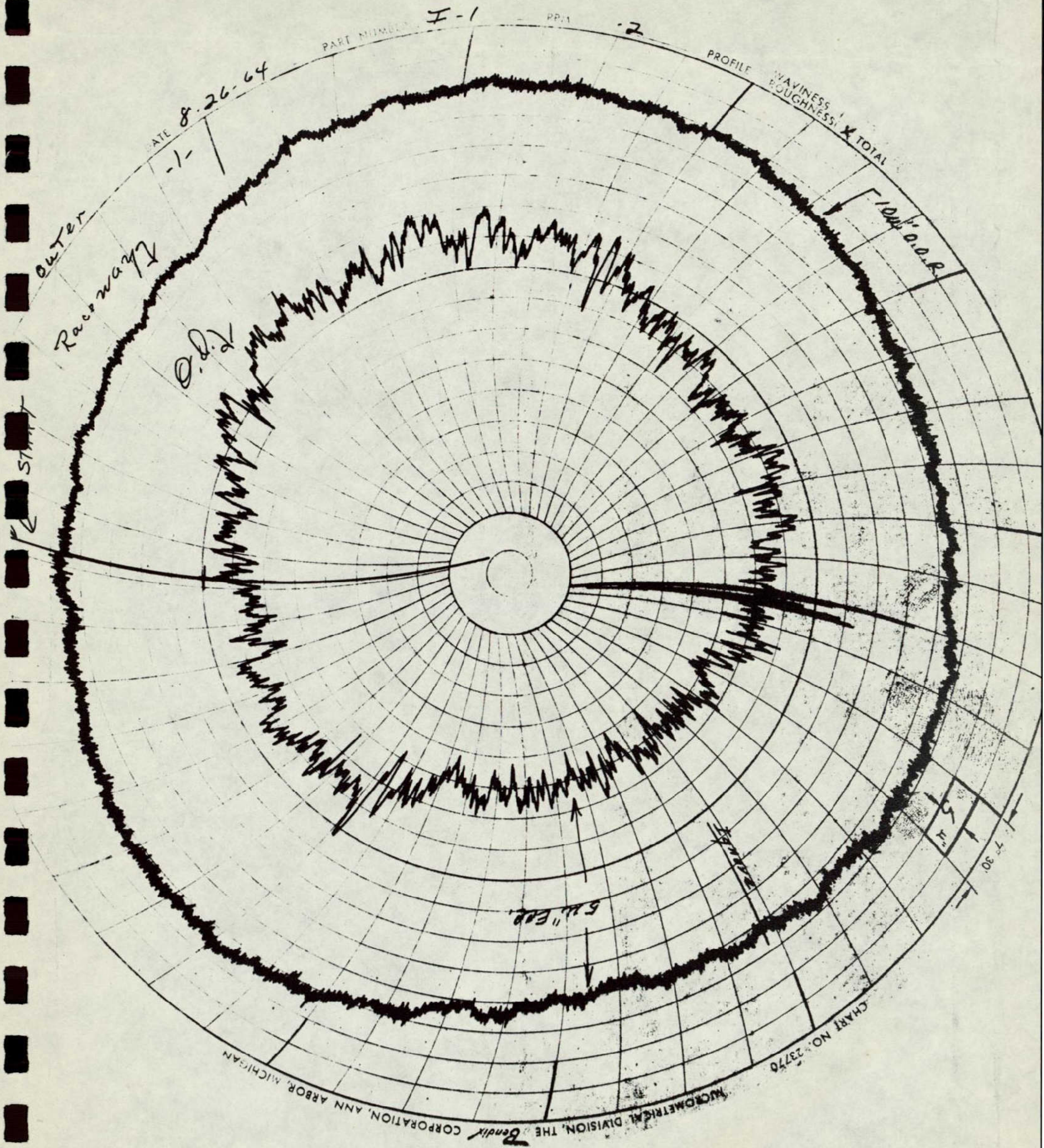
Phase II



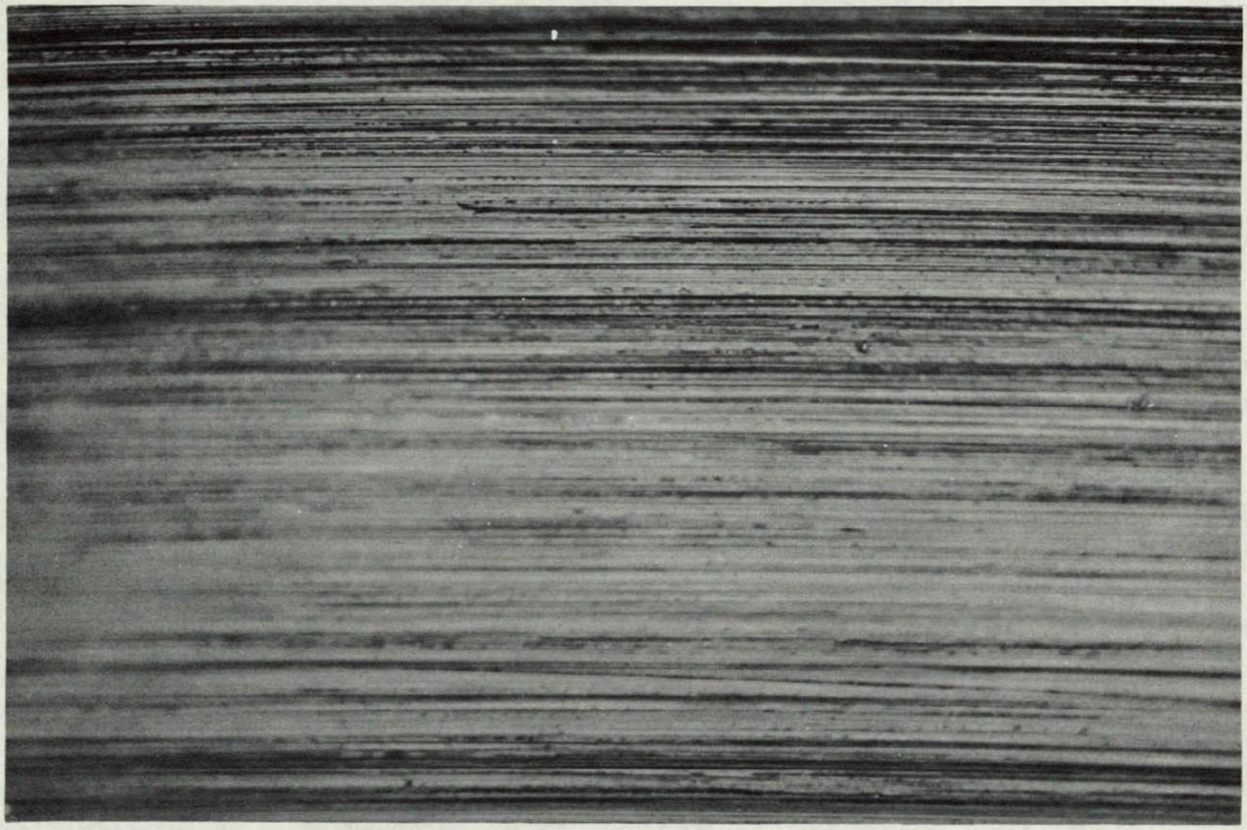

PROFICORDER TRACES OF INNER RACE OF LOT I , BRG. 1



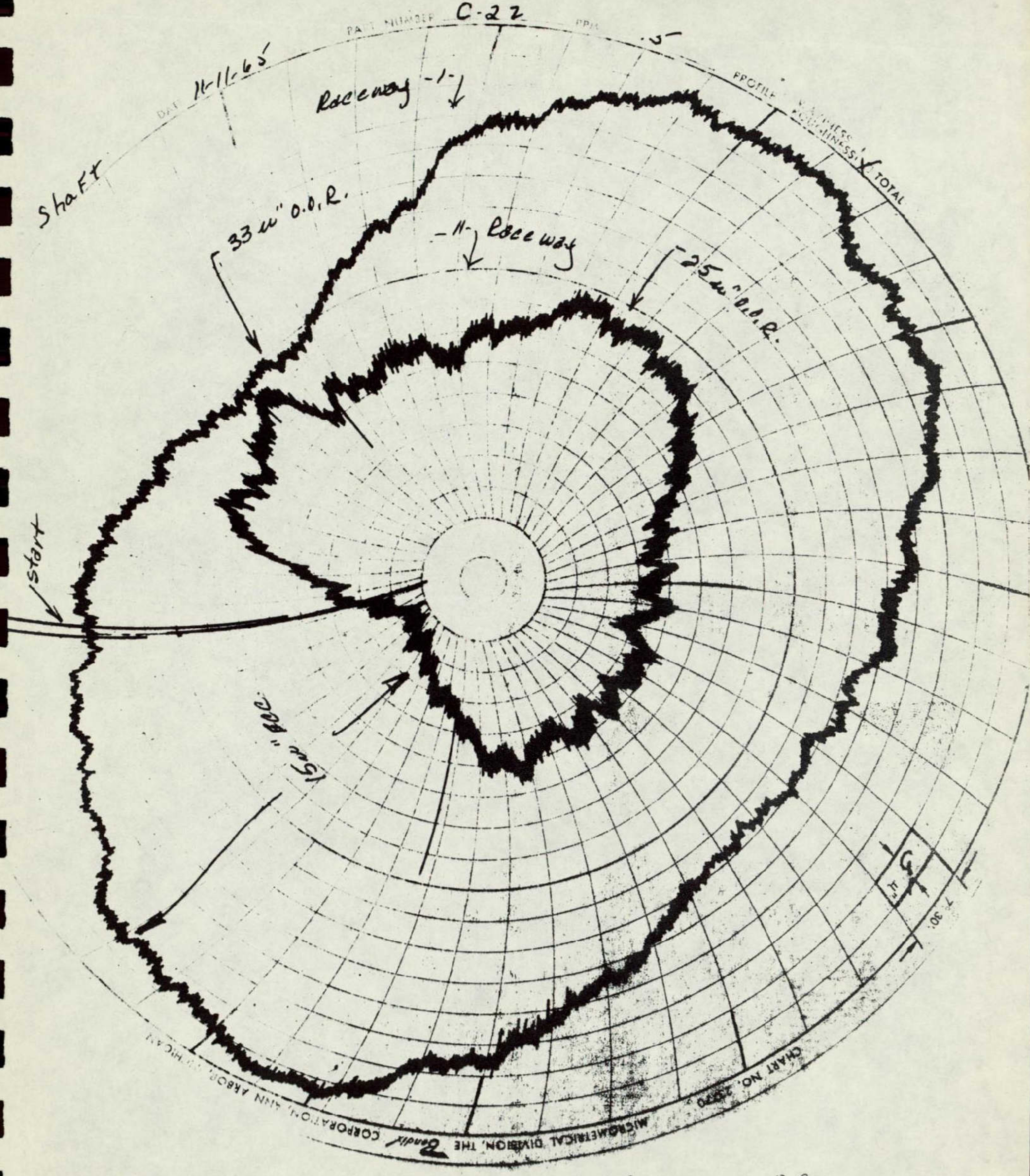

PROFICORDER TRACES OF OUTER RACE OF LOT I , BRG. 1




PROFICORDER TRACES OF OUTER RACE OF LOT I , BRG. 1

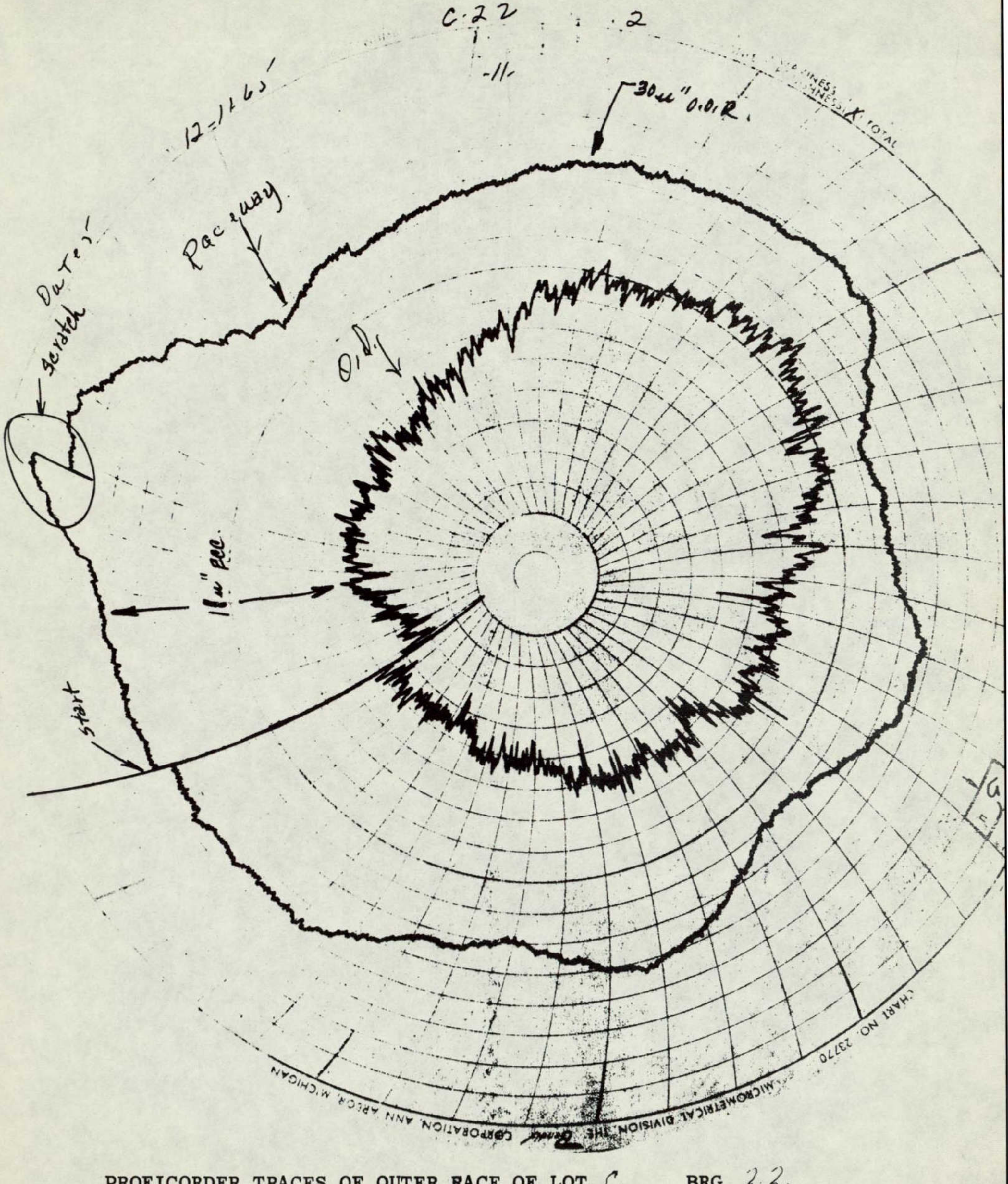


MRC C 22
Shaft #2 Side 400 X
Phase III



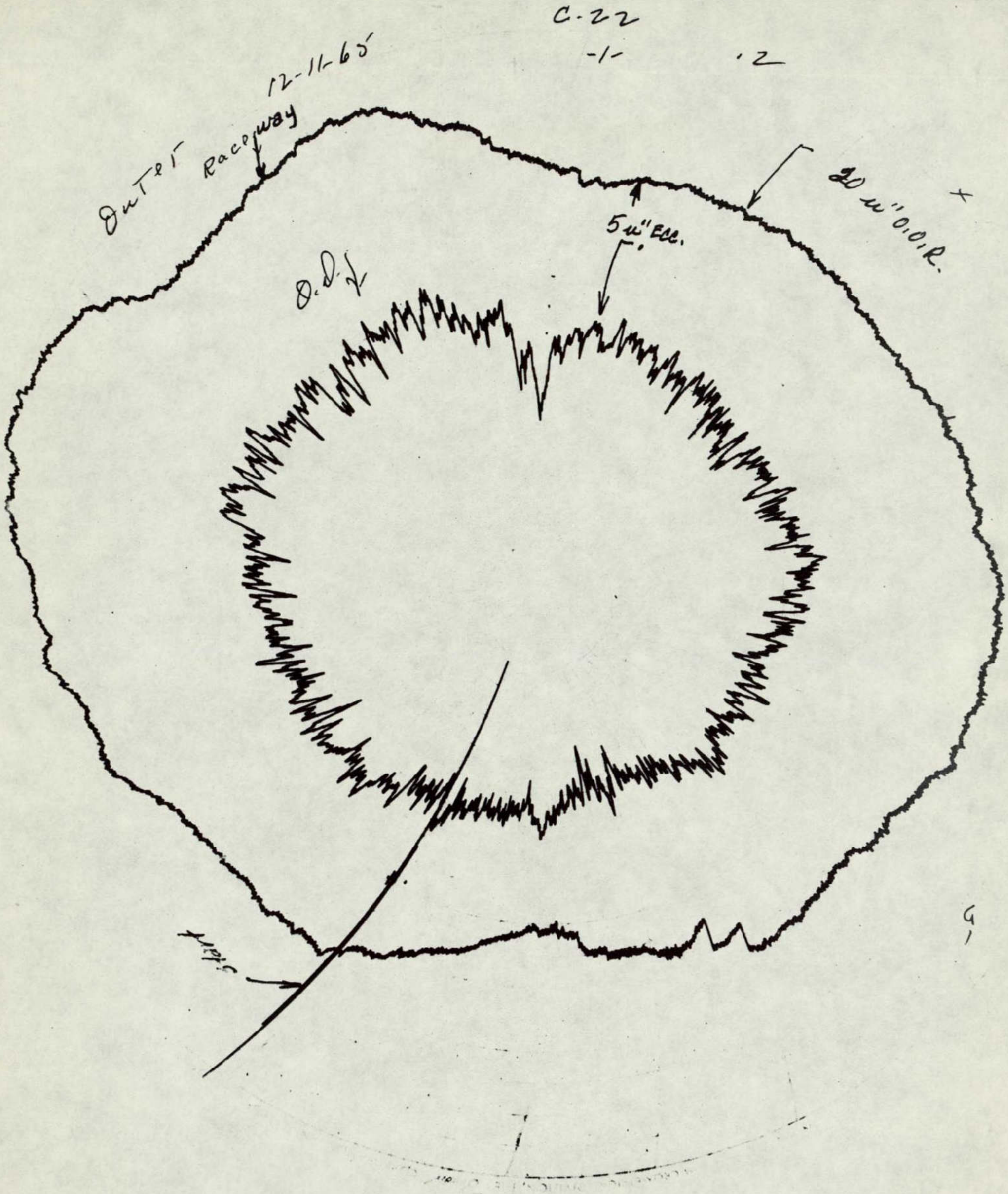

PROFICORDER TRACES OF INNER RACE OF LOT C , BRG. 22

PHASE III



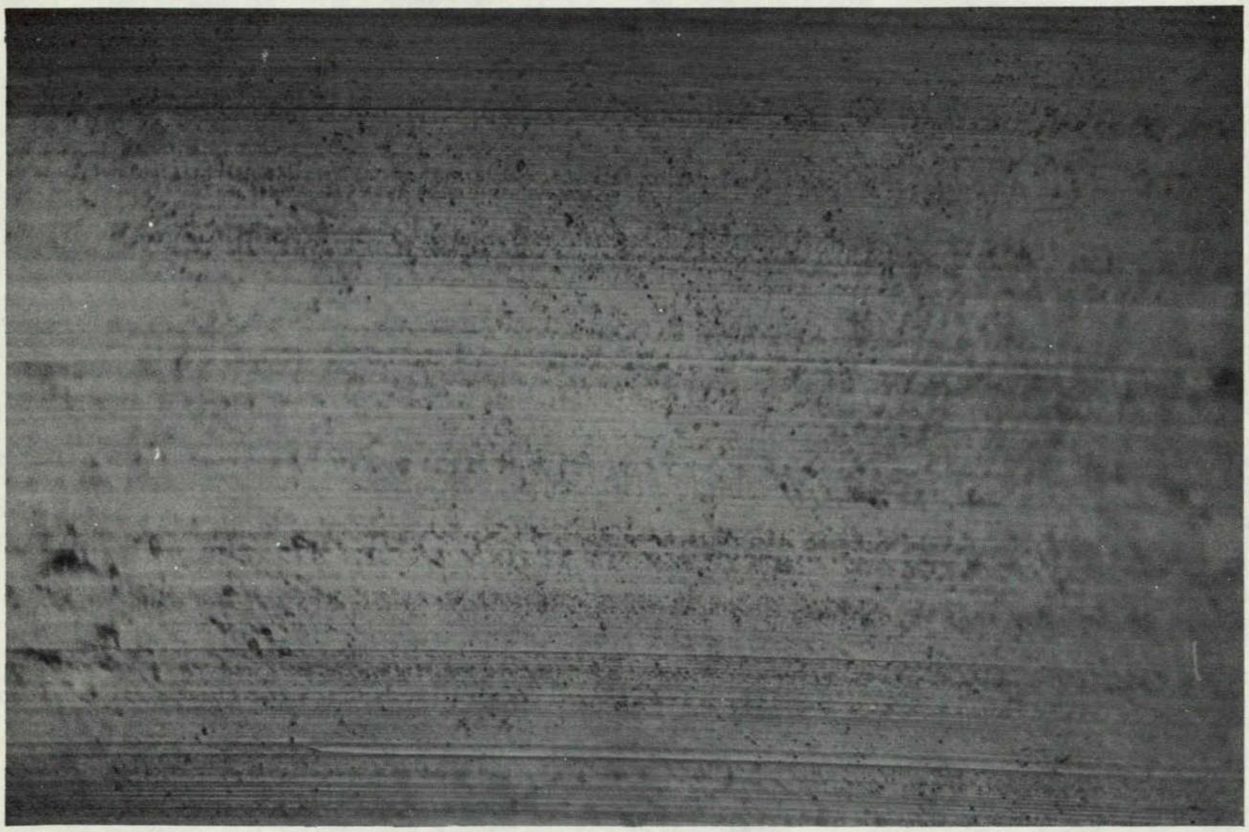

PROFICORDER TRACES OF OUTER RACE OF LOT C , BRG. 22

PHASE III

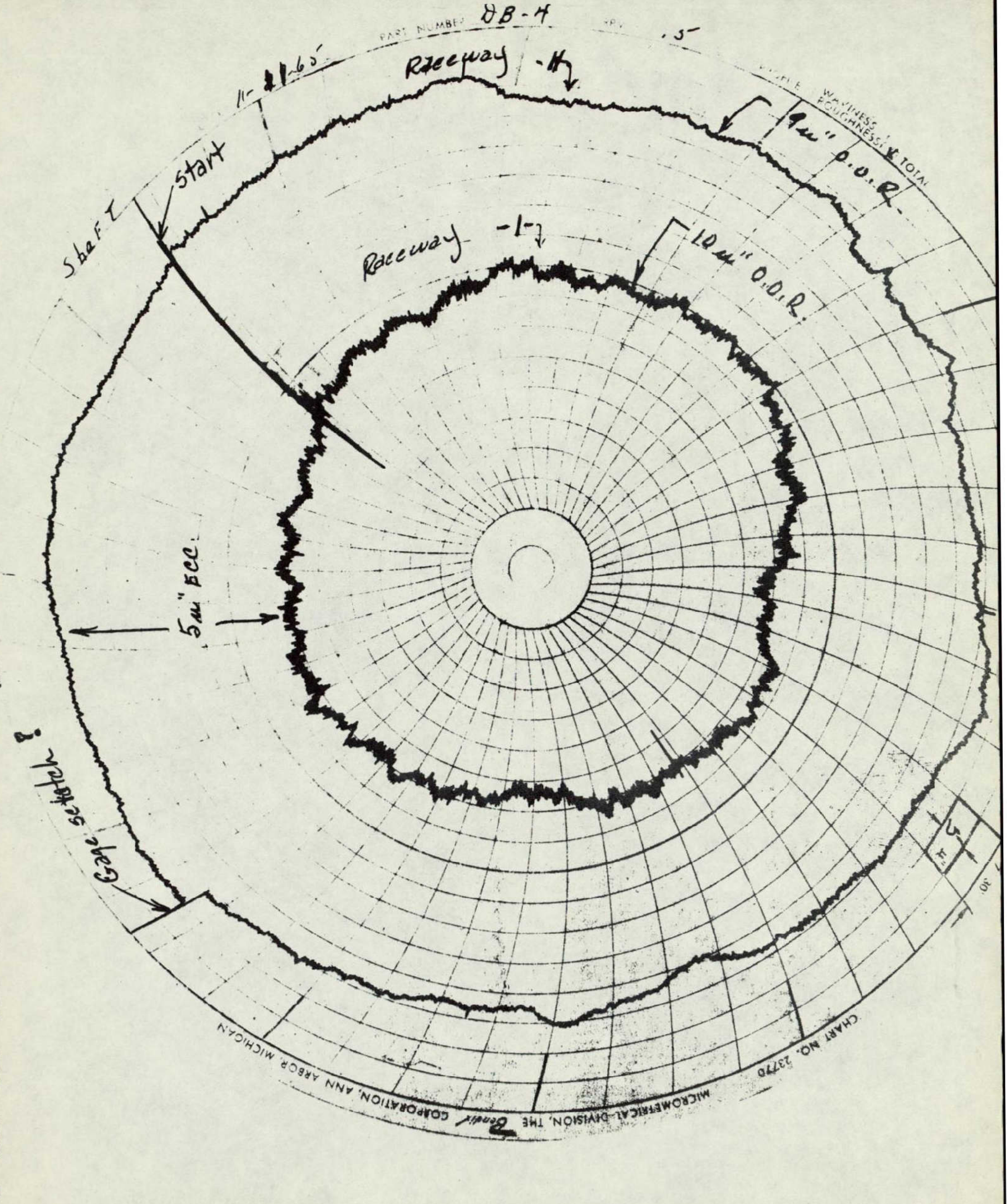



PROFICORDER TRACES OF OUTER RACE OF LOT C , BRG. 22

PHASE III

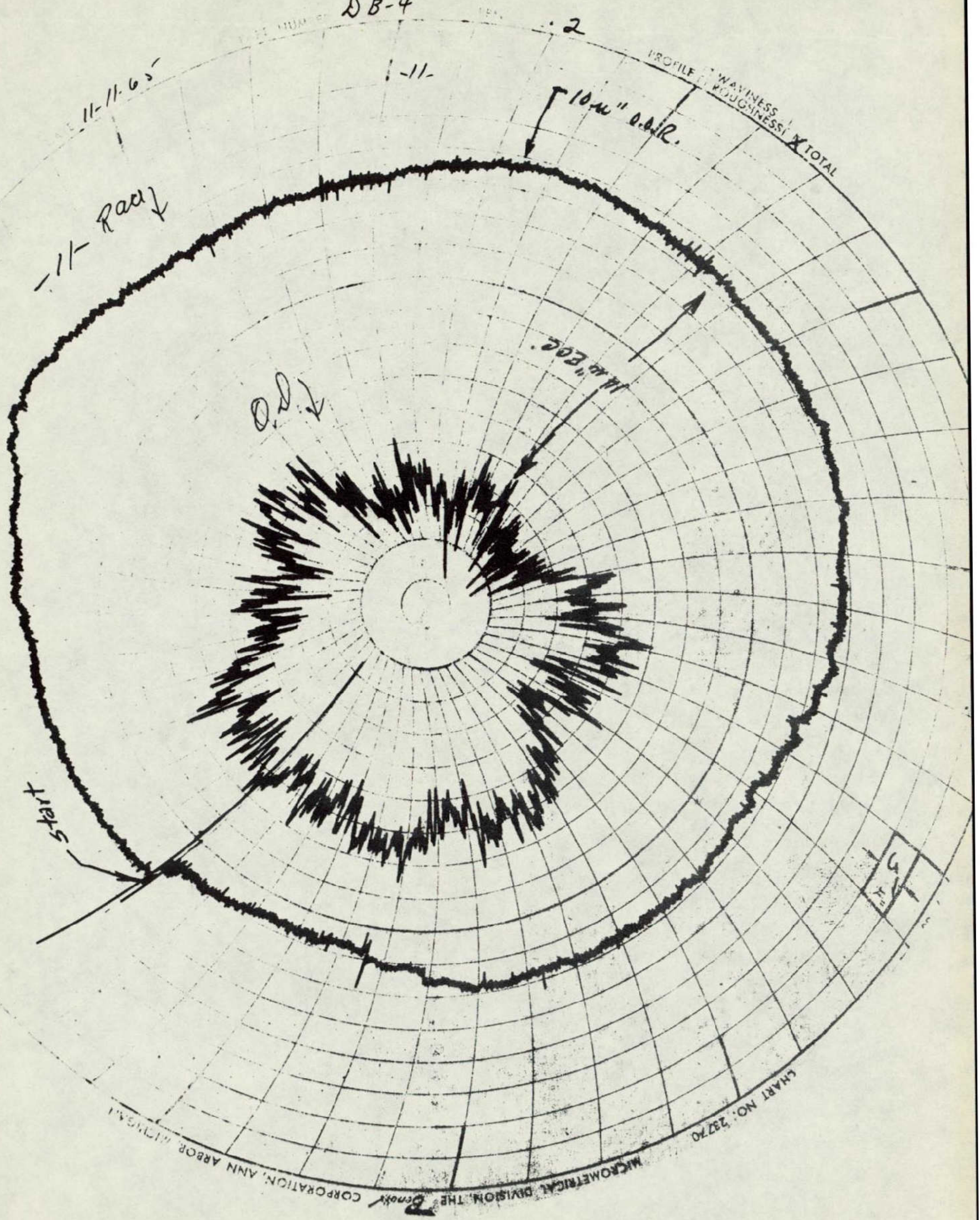


MRC DB 4
Shaft #2 Side 400 X
Phase III

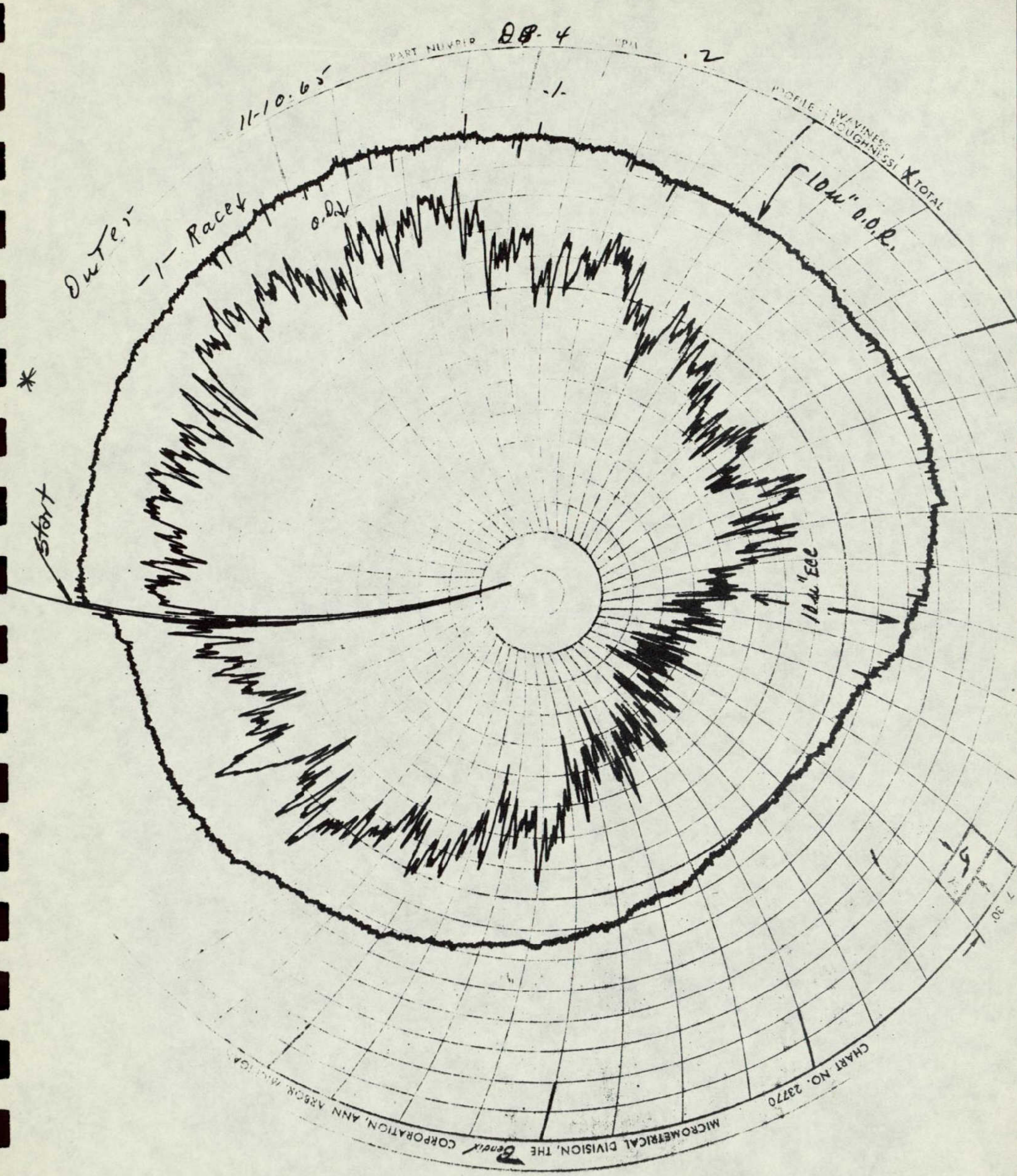



PROFICORDER TRACES OF INNER RACE OF LOT DB , BRG. 4

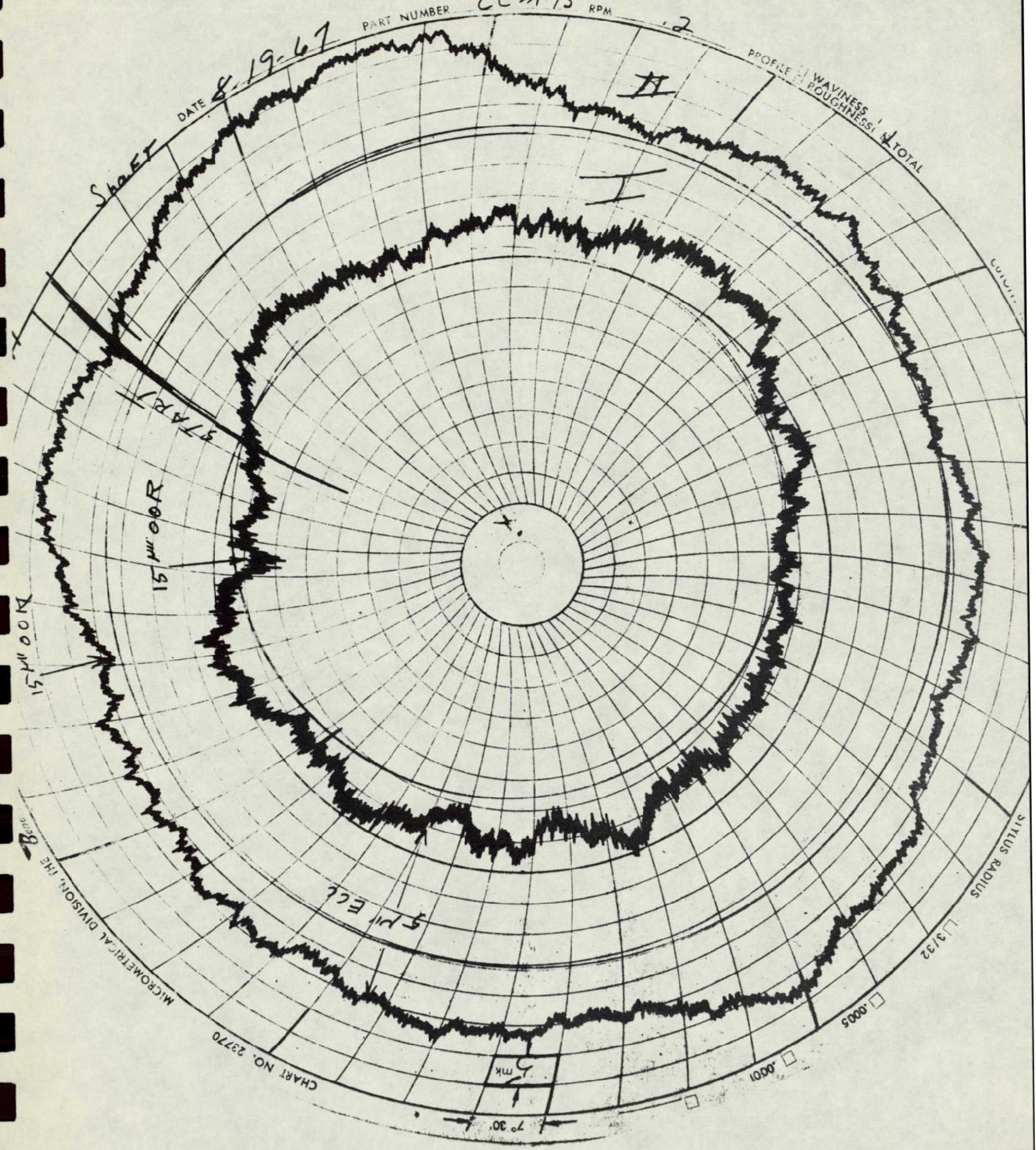
PHASE III



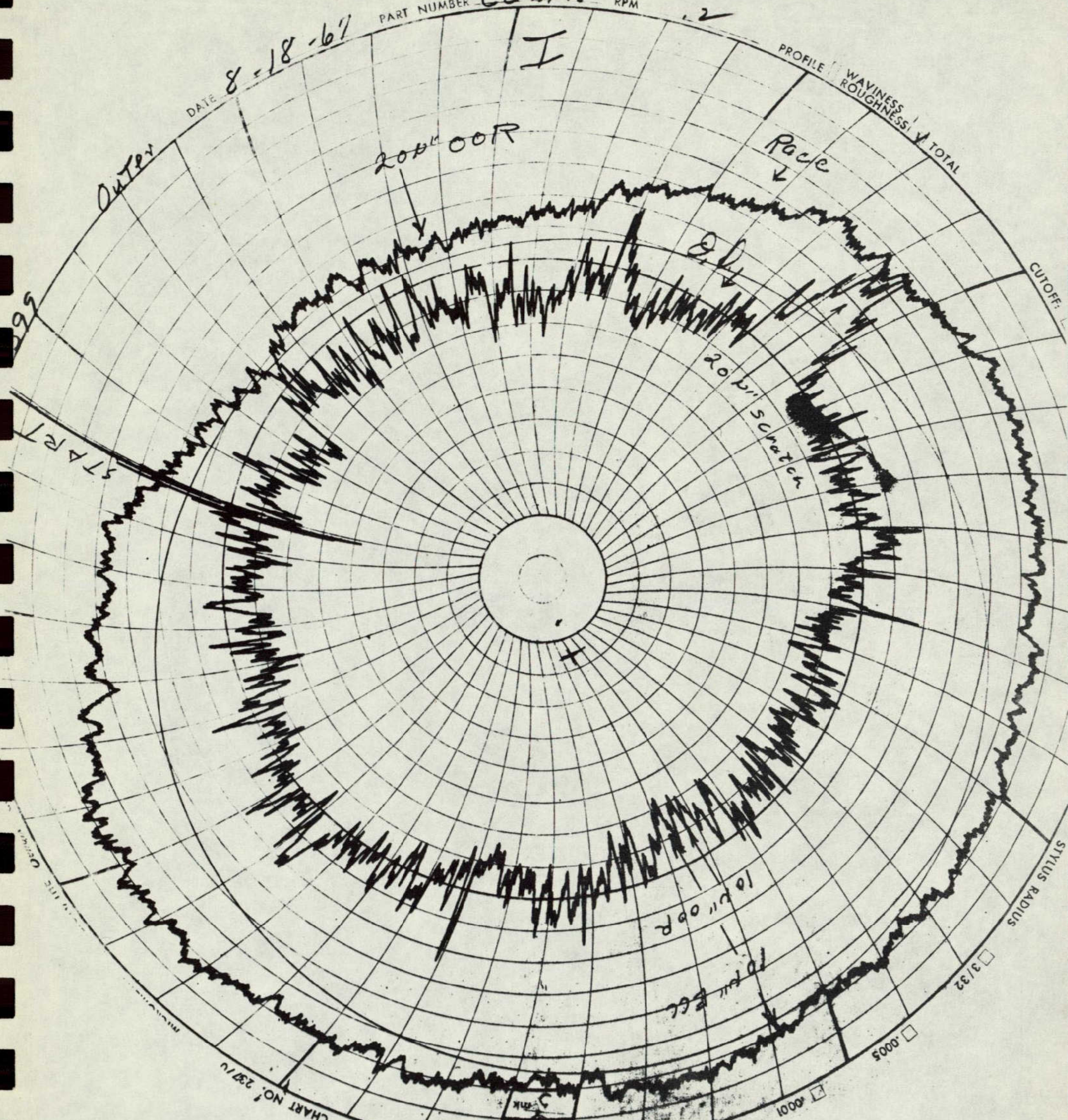

PROFICORDER TRACES OF OUTER RACE OF LOT DB , BRG. 4
PHASE III



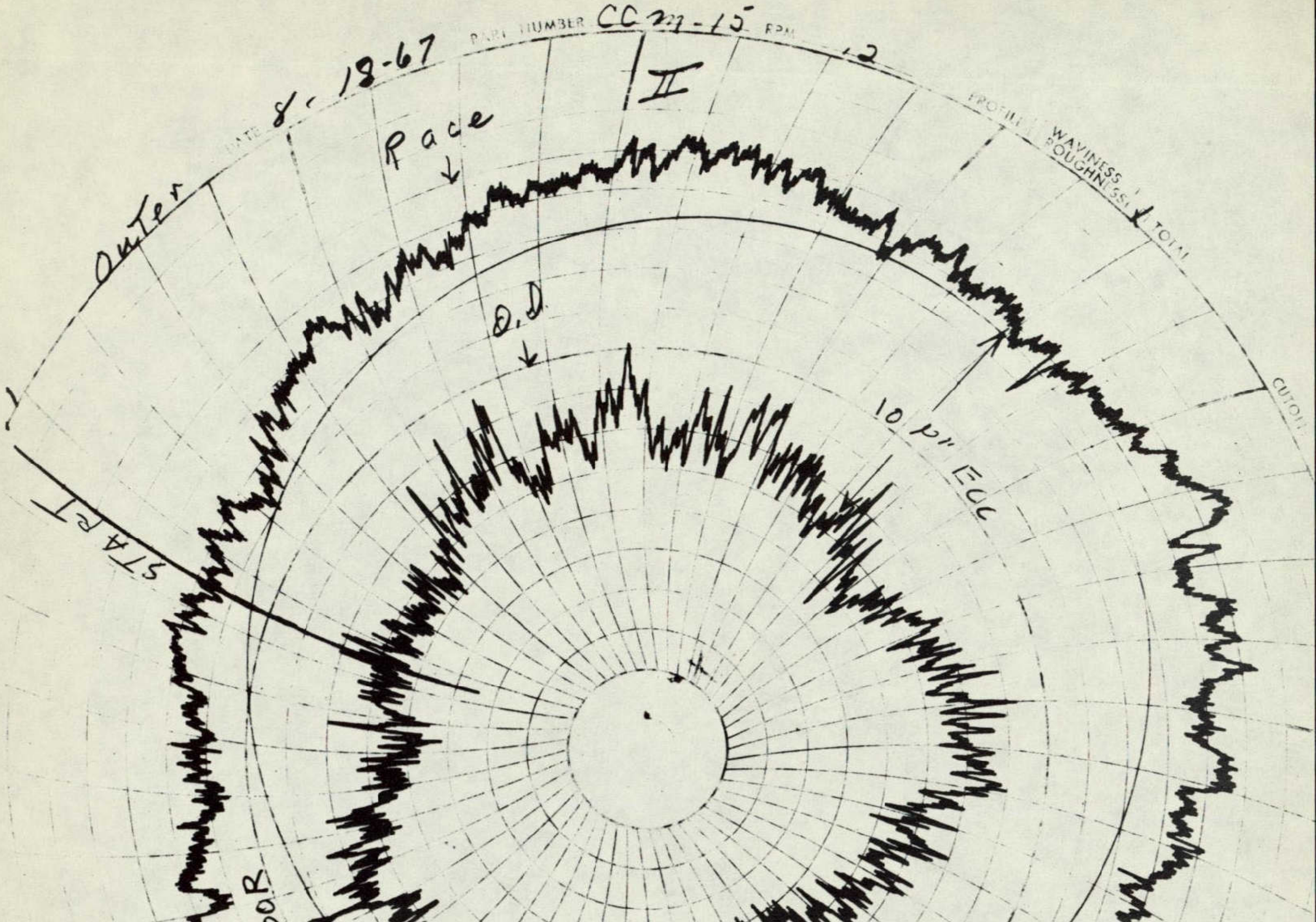

PROFICORDER TRACES OF OUTER RACE OF LOT DB , BRG. H
PHASE III




PROFICORDER TRACES OF INNER RACE OF LOT CCM ,BRG. 15
PHASE V




PROFICORDER TRACES OF OUTER RACE OF LOT CCM, BRG. 15
PHASE V




PROFICORDER TRACES OF OUTER RACE OF LOT CCM, BRG. 15

PHASE V