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FINAL REPORT

WEAR RATES OF FINAL DRIVE SUN GEAR BY RADIOACTIVE METHOD

Frank L. Schwartz
Supervisor

Robert H. Eaton
Project Engineer

Ardath H. Emmons
Assoc. Radiological Safety
Officer

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CONTENTS

SUMMARY

A method is described in this report by which rates of gear wear, under different conditions, can be obtained by the use of the radioactive tracer technique.

This method makes possible the continuous determination of rates of gear wear at all loads and speeds in actual full-scale units. In this investigation the radioactive tracer technique has been used to find the wear rate of the landing-craft final-drive sun gear, when a straight mineral oil and an extreme-pressure gear lubricant are used.

WEAR RATES OF FINAL-DRIVE SUN GEAR BY RADIOACTIVE METHOD

INTRODUCTION

The rate of gear wear varies with speed, load, lubrication, and heat treatment of the metal used in the gear. Older methods of determining wear consisted of operating a gear under various load conditions and visually observing or measuring the surface of the gear. By this method little information concerning the rate of wear was obtained. Only those critical loads or speeds where accelerated or destructive wear began were observed.

The radioactive method of measuring gear wear gives a quantitative method of measuring the minutest amount of wear at loads and speeds much below critical destructive conditions. Wear rates as low as 50 micrograms per minute can be detected. Also the amount of metal transferred from a pinion to its mating gear can be detected. Rate of wear can be measured continuously; thus loads and speeds can be changed frequently and wear rates determined for a large number of operating conditions in a short period of time, many hours being saved in making an extended analysis of gear failure.

THE RADIOACTIVE METHOD OF MEASURING GEAR WEAR

This method for determining wear rates in gears consists of activating a sample gear in a nuclear reactor. During the exposure of the gear some elements in the gear material are changed to other radioactive isotopes, principally Fe-59 and Fe-55. The half life of Fe-59 is 46 days; that of Fe-55 is 2.9 years. Iron powder obtained by grinding the side of the gear is carefully weighed, wrapped in aluminum foil and inserted in the gear so that it receives the same exposure in the nuclear reactor as the gear. For purposes of calibration, the activated iron powder is then mixed with a known quantity of oil and circulated in a closed system as shown in Fig. 1. The concentration of radioactive iron is known and the reading of the detector-ratemeter-recorder unit is a direct measure of the concentration of iron in the oil. By adding successive known amounts of iron to the oil, a calibration curve (Fig. 5) of counting rate versus iron concentration is obtained.

The intensity of radiation from a given weight of iron decreases logarithmically with time. However, by setting aside a small sample of the metal and measuring the activity of this sample periodically, it is possible to correct all data to zero time. Figure 5 shows this decay correction curve. There are two sets of data plotted on Fig. 6. The top curve shows the intensity decrease of a sample measured with only air between the detector and specimen. The lower curve shows the intensity decrease with an absorber between the detector and specimen. Of course, the lower curve represents the actual situation when measuring the activity in oil in a closed system with an external detector. The two sets of data are reproduced to point out a possible pitfall to the unwary operator using these techniques.

As the radioactive gear is operated under a prescribed load and speed, the particles of iron worn off circulate with the oil. The meter intensity then indicates the concentration of iron in the oil. By plotting a continuous graph of iron concentration versus time, the rate of wear can be determined from the slope of the curve. The rate of wear can be measured during any time interval long enough to draw an accurate slope through the plotted data.

PROCEDURES

Calibration Procedure

An experimental sun gear made for the No. 1206258 final-drive assembly was used in the radioactive-gear tests. This experimental sun gear was a standard width involute gear with a 0.040 modification of the tooth profile. The material was No. TS8620 steel from Youngstown Sheet and Tube heat No. 29585. The chemical analysis of this steel is as follows:

C........0.23
Mn.......0.85
Si.......0.29
Ni.......0.48
Cr.......0.67
Mo.......0.11

After the final manufacturing process, the gear was given a coating of Parker Lubrize 0.001 inch to 0.003 inch thick.

Another gear from the same steel lot was used to make up a calibration sample. A fine, high-speed grinding wheel was used to grind about three grams of metal from one end of the gear. This powder was collected by a magnet placed close to the off side of the grinding wheel. Samples of this powder were carefully weighed, wrapped in pure aluminum foil and placed in the bore of the gear so that the sample and the gear received the same neutron bombardment. A similar sample of the powder ground from the gear was washed with carbon tertrachloride and alcohol to remove all oil films and then photographed under 110x magnification, Fig. 18. One package contained 113 milligrams, another contained 311.5 milligrams and the third contained 792 milligrams. The gear and the samples were then sent to Oak Ridge, Tennessee, where they were placed in the reactor for 28 days. At the end of this time the gear and samples were returned to the University. Daily readings were taken with a Geiger-Müller counting tube and scaler to determine the decay rate. During the first few days the decay rate was high because of the effect of the elements with short half-life periods. After about ten days the activity decreased in a straight-line relationship and the test was begun.

The calibration oil system, Fig. 1, was started with one gallon of oil in the system and readings were taken to establish the background level. With the oil still circulating, the smallest package, containing 113 milligrams of the gear-metal powder, was added to the system. The calibration system was checked periodically until the activity level became constant, indicating an even distribution of the powder in the oil. This reading was recorded. Next, another gallon of oil was added to the system. After a short time necessary for complete mixing, the system's activity was determined and recorded. Next, the 311.5-milligram sample was added to the system making a total of 424.5 milligrams in 2 gallons of oil. This quantity was circulated and a reading taken. Next, the 792-milligram sample was added, and circulated, and a reading was taken. Another gallon of oil was then added, and mixed, and a reading was taken. From the above data, the curve of Fig. 5 was made, showing activity versus milligrams of metal/gallon of oil. With this plot, any reading of activity in the identical counting chambers used on the actual oil system can be converted to milligrams of metal/gallon of oil. If the tests cover a period of several days, it is necessary to apply corrections for the decay of the radioactivity. This can be done by determining the calibration-system activity and drawing through this point a curve parallel to the original curve of activity versus weight of metal. The calibration system per gallon of oil is shown in Fig. 19. The above calibration procedure was followed for both counting chambers. The larger counting chamber provided an increase in sensitivity by a factor of 10 because of the increased amount of radioactive material around the Geiger-Müller tube.

Test Procedure

The radioactive sun gear was installed in the No. 1206258 final drive by means of special long-handled tongs. The four-square, or locked torque-testing device was reassembled as shown in the photograph, Fig. 23, and in Fig. 3. The oil system was filled with four gallons of SAE No. 30

mineral oil. Table I gives the loads, speeds, and running times of the tests which were run on the radioactive sun gear using SAE No. 30 mineral oil. These data are shown in Figs. 7 and 8.

TABLE I

Lubricant: SAE No. 30 mineral oil

Load	Speed	Time
500 ft-lb	500 rpm	34 minutes
500	750	55
500	800	90
1000	500	60
2000	800	60
4000	800	25
	(drop gear box failure)	
3000	400	30
3000	1000	30
3000	800	21
3000	1200	27
4000	400	18
4000	800	30
4000	1000	18
4000	1200	9
4500	400	18
4500	800	28
4500	1000	12
5000	400	39
5000	800	27
5000	1000	12
5000	1200	12
	Total	650 minutes 10.83 hours

At the end of the 10.83 hours described in Table I, the sun gear was badly worn. The wear rate had increased until 99 milligrams of metal were being worn off per minute at a speed of 1200 rpm and a load of 5000 ft-lb. At this point it was decided to see what effect a change to an extreme-pressure type of lubricant would have on this high wear rate of the worn out gear. The system was flushed thoroughly, checked for residual radioactivity, and refilled with 4 gallons of Texaco EP No. 80 gear lubricant. Table II gives the loads, speeds, and running times of the tests with the worn sun gear but with new EP No. 80 gear lubricant. These data are shown in Fig. 9.

TABLE II

Lubricant: EP No. 80

Load	Speed	Time
3000 ft-lb	400 rpm	48 minutes
3000	800	21
3000	400	6
3000	800	18
3000	1000	45
4000	1200	15
4000	400	15
4000	800	39
4000	1000	18
4500	1200	24
4500	400	15
	Total	264 minutes

The wear rate decreased considerably due to the use of the extreme-pressure gear lubricant. The radioactivity measurements were erratic during the run because of the flaking off of pieces of metal caused by fatigue during the previous run. The average wear rate, however, decreased due to the change to the extreme-pressure lubricant. At this point the entire system was disassembled, cleaned, and inspected. New sun planet gears were installed. The radioactive sun gear was reversed so that the other side of the teeth would now mate with the new set of sun planet gears. The system was reassembled and run under the conditions described in Table III.

TABLE III

Lubricant: Texaco EP No. 80

Load	Speed	Time
500 ft-lb	500 rpm	33 minutes
500	750	60
500	500	90
1000	500	60
2000	800	60
3000	800	60
3000	400	75
3000	800	29
3000	1000	18
3000	1200	13
4000	400	3

(stopped because of bearing failure in other final drive)

TABLE III (CONTINUED)

Lubricant: Texaco EP No. 80

Load	Speed		Time
500 ft-lb	800 rpm		39 minutes
4000	400		30
4000	800		27
4000	1000		24
4000	1200		18
4500	400		30
4500	800		36
4500	1000		15
4500	1000		30
1000	500		55
3000	400		30
3000	800		25
3000	1000		21
3000	1200		9
3000	940		42
3000	800		54
3000	1000		54
3000	1200		27
4000	400		12
4000	800		26
4000	1000		21
4000	1200		27
5000	400		21
5000	800		17
5000	1000		19
5000	1200		15
6000	400		18
		Total	1243 minutes 20.71 hours

A bearing on the outboard side of a planet-gear shaft failed during the 6000-lb-ft run. This failure caused added load on the sun gear, resulting in a fracture thru the hub of the sun gear. The tests were discontinued at this time.

At the conclusion of the wear tests a study was made of the metal transferred to the planet gears which mate with the radioactive sun gear. The planet gears were first cleaned and dried. A strip of Kodak no-screen dental x-ray film was placed in intimate contact with the tooth surface for 24 hours. At the end of this time the film was developed and printed. This procedure was followed on gears from the mineral-oil test and from the extreme-pressure-lubricant test. The results are shown in Fig. 32. These radiographs indicate a great amount of metal transfer when using a straight mineral oil but comparatively little transfer when using an extreme-pressure oil.* In both cases little transfer of metal occurred at the pitch line because of rolling contact.

SPECIALIZED RADIOACTIVE-GEAR TEST EQUIPMENT

The special radiation-detection equipment used in these tests can be divided into two categories: (1) required health-protection instrumentation and (2) necessary detection and measurement instrumentation.

The health protection equipment includes the following:

1 model 2611P survey meter from Nuclear-Chicago
1 model SRJ-1 survey meter from Technical Associates

The first instrument is a low-level detector covering the range of 0 to 20 milliroentgens per hour and is used primarily to check for radioactive contamination. The second is a higher-range instrument covering the range of 0 to 5000 milliroentgens per hour. This instrument is used to evaluate permissible operating times quantitatively in given locations.

Each man in the vicinity of the tests was required to wear a film badge and a quartz-fiber electroscope. The quartz-fiber electroscope gave an immediate check on the exposure of personnel to radiation while the film badge gave the total exposure to radiation.

The second instrument group includes those required to detect and record quantitatively the activity in the oil system. The instruments used in this work are the following:

odel 6303 detector tubes from Victoreen
odel SC-34 rate meter from Tracerlab
odel A. W. -1 MA recorder from Esterline-Angus
odel L-75 analysis unit from Landsverk

*It should be noted also that the gears which had been used with straight mineral oil had only half the running time as the set run with EP 80, but indicated much more transferred metal.

DISCUSSION OF RESULTS

The wear rates and total wear are shown in Figs. 7, 8, 9, 10, 11, 12, and 13. In general, the wear rate increases with both load and speed. At some intermediate loads the wear rate was greater at 400 rpm than at 1000 rpm. Journal-bearing studies have shown that the thickness of the oil film when operating in the hydrodynamic or thick-film range depends directly on the absolute viscosity of the oil and the speed and inversely on the load. It is from this relationship that the possibility arises for increased wear rates at lower speed.

The data in Fig. 7 shows an interesting verification of high initial wear rates. This high initial wear rate is caused by actual contact of the higher asperities of the tooth surfaces. The first indication of wear occurred within five minutes of the start of the test at the low load of 500 ft-lb and 500 rpm. This high initial wear rate dropped to half its original value in fifteen minutes and to approximately zero in two hours. This is about the time in which past tests have shown a high polish to be produced on the tooth surfaces.

The wear rate is plotted versus speed in Fig. 14 for SAE 30 mineral oil and in Fig. 15 for EP 80 gear lubricant. No measureable wear was found below 5000 ft-lb when using EP 80 gear lubricant. The maximum wear rate shown for EP 80 gear lubricant was 4.7 milligrams per minute at 5000 ft-lb torque and 1200 rpm. In order to keep the wear rate within this range when using SAE 30 mineral oil, the speed would have to be limited to 1060 rpm at 3000 ft-lb, 660 rpm at 4000 ft-lb, 400 rpm at 4500 ft-lb, 300 rpm at 5000 ft-lb. Even at this reduced speed there is danger of rapid wear due to oil-film breakdown at low speeds as explained above. If a speed of 1200 rpm were used it would be necessary to limit the load to approximately 2500 ft-lb to keep within the same wear rate found for the gear at 5000 ft-lb when using the EP 80 gear lubricant.

The particle size of the powder ground from a gear for calibration purposes is of interest. Figure 18 shows photomicrographs of the particles magnified 110 times. Some of the particles became molten during grinding and congealed into spheres, in others only the ends melted, and others have the form of chips. The largest particles have an average dimension of about 0.002 in. It was found necessary to keep a fairly high oil velocity in the calibration system in order to keep the particles in suspension. By placing a Geiger-Müller counter at various points of the calibration system a check could be made to determine whether there was an accumulation of particles at any point. The tubing, fittings, and counting chambers were designed to prevent the settling of the metal particles. When the oil velocity was maintained above 600 ft/min all particles remained in suspension. No effort was made to determine the size of wear particles removed from the gear. During normal wear it is reasonable to expect these particles to be very minute, perhaps of molecular size. At very heavy load with SAE 30 oil, particles of large size, larger than the calibrating particles, broke from the gear face due to surface fatigue. These large particles showed up as erratic readings on the radioactivity chart. When first noticed, these irregular traces on the chart could not be explained satisfactorily. A complete check of all instrumentation proved that all instruments were indicating properly. Further inspection showed that the traces were due to the large particles which spalled off the gear. It should be noted, however, that in spite of the irregularity in the radioactive trace, a definite slope and therefore wear rate could be measured. This type of trace was most noticeable after the high loads with SAE 30 mineral oil.

Table IV gives the wear rates found in the tests.

TABLE IV

WEAR RATE

Load ft-lb	Speed rpm	MGM/minute Mineral Oil	EP 80
6150	400	---	5.7
5000	1200	99.0	4.7
5000	1000	77.7	1.9
5000	800-	30.0	1.02
5000	400	14.4	0.21
4500	1200	59.5	---
4500	1000	37.0	---
4500	800	18.9	---
4500	400	18.2	---
4000	1200	42.6	---
4000	1000	14.8	---
4000	800	8.25	---
4000	400	27.7	---
3000	1200	15.0	---
3000	1000	3.14	---
3000	800	1.67	---
3000	400	1.17	---

RECOMMENDATIONS

This experiment has shown conclusively the superiority of the EP 80 gear lubricant over the straight mineral oil for this particular application. (Characteristics of EP 80 lubricant are listed below.) Past tests have substantiated this same conclusion but have always been accompanied by doubts due to the possibility of error caused by differences in heat treatment, gear geometry, alignment, and numerous other variables. On the basis of the past conventional wear tests and this radioactive gear test, the use of an EP oil for this application is strongly recommended.

It is further recommended that the radioactive tracer technique be considered as the method of choice in future gear-life or lubricant studies. The method as outlined in this report results in a great saving of time and money over the conventional gear-wear tests, besides providing information which cannot be obtained otherwise.

TEXACO UNIVERSAL GEAR LUBRICANT - EP 80

SAE Number	80
Gravity, °A.P.I.	24.7
Flash, Open, °F	410
Pour, °F	-30
Color, ASTM	Dk. Green
Viscosity at 100°F, sec	406
Viscosity at 130°F, sec	185
Viscosity at 210°F, sec	58
Viscosity Index	93
Sulphur, %	0.72
Chlorine, %	1.61
Phosphorus, %	0.024
Lead, %	-
Ash, %	Trace
Water, %	Nil
Almen Pin Rating, psi	26,000
Corrosion Strip, 3 hours at 212°F	Pass
Channel Test	Channeled at -60°F

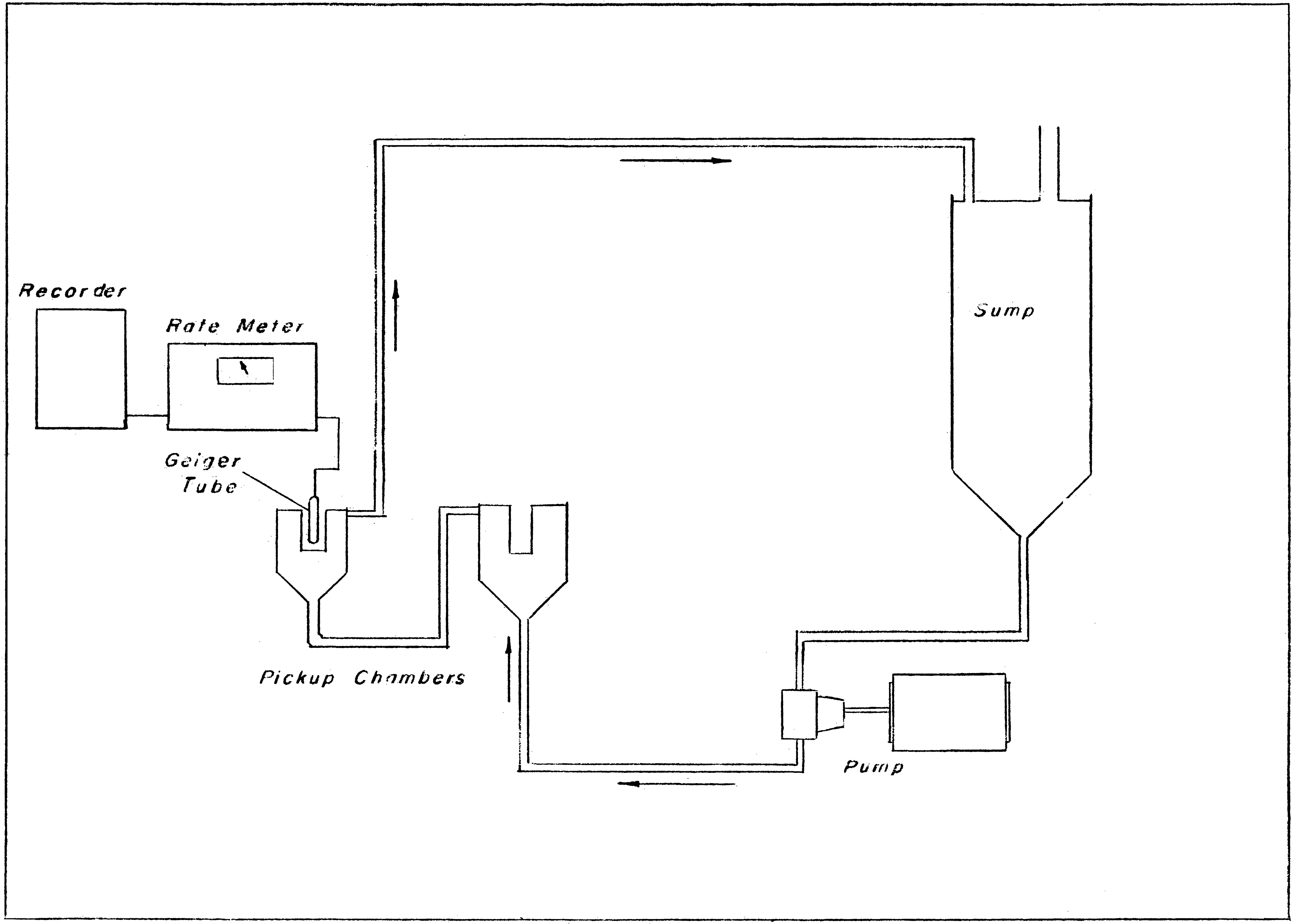


Fig. 1. Calibration System

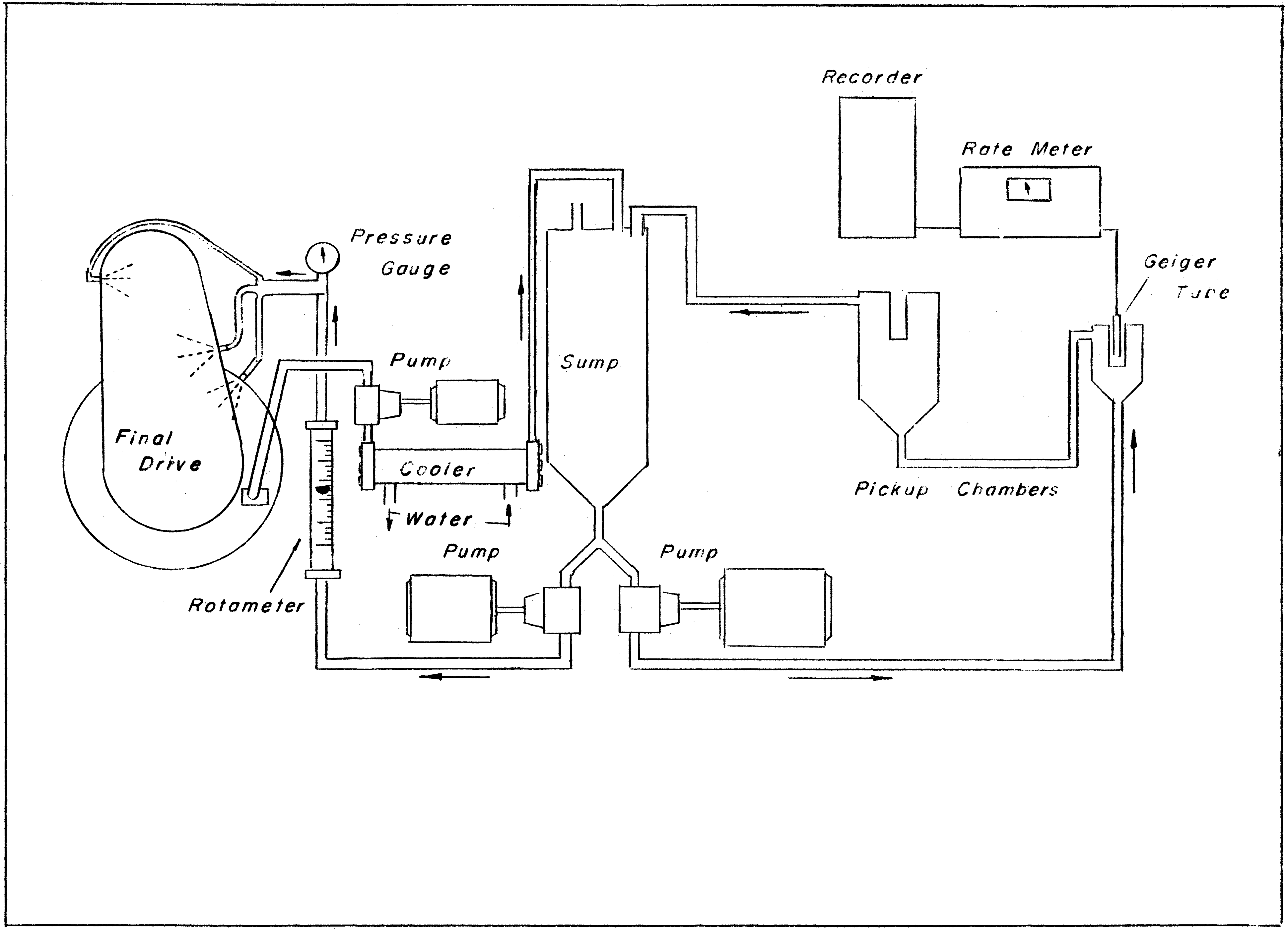


Fig. 2. Testing System

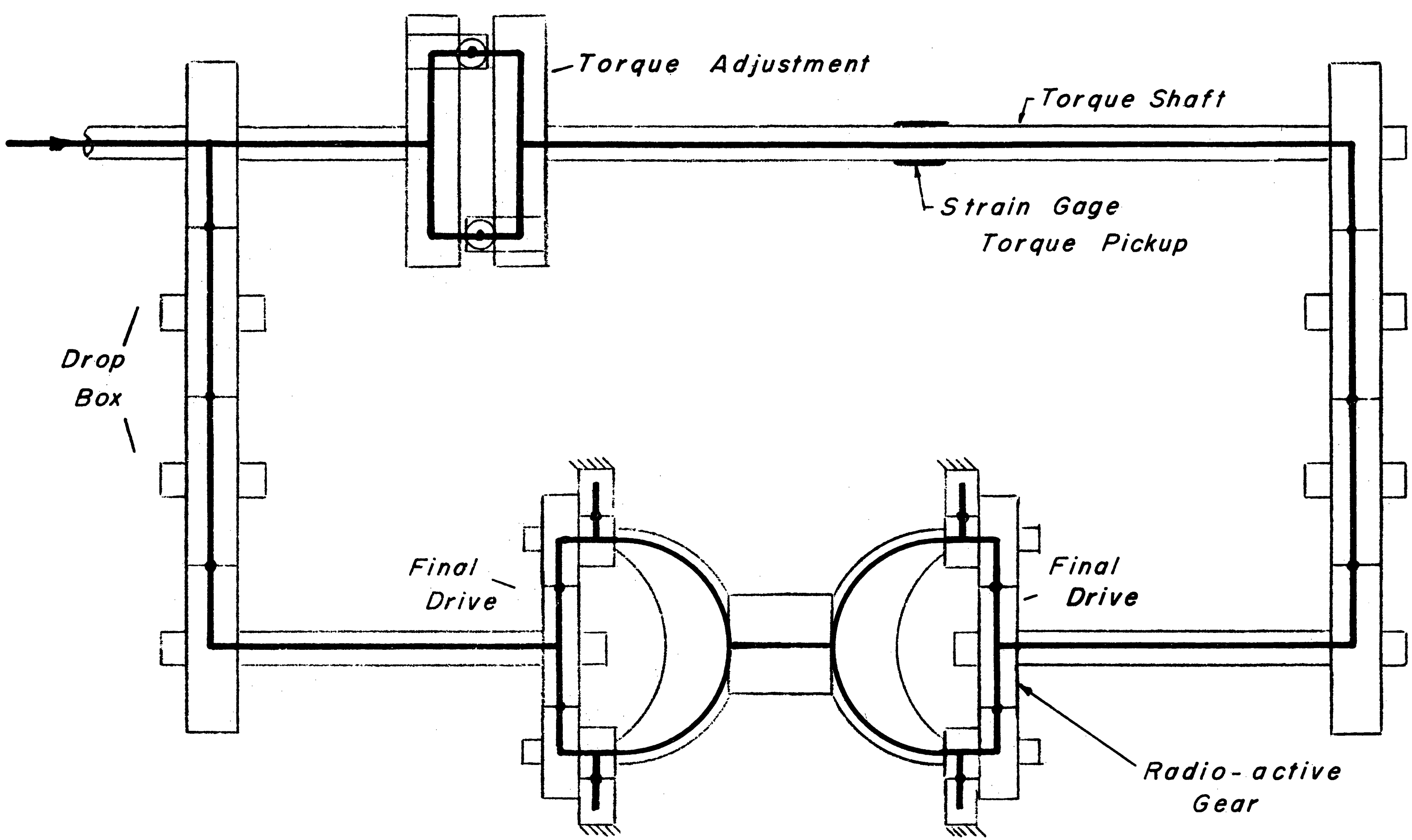


Fig. 3. Four Square Testing Arrangement

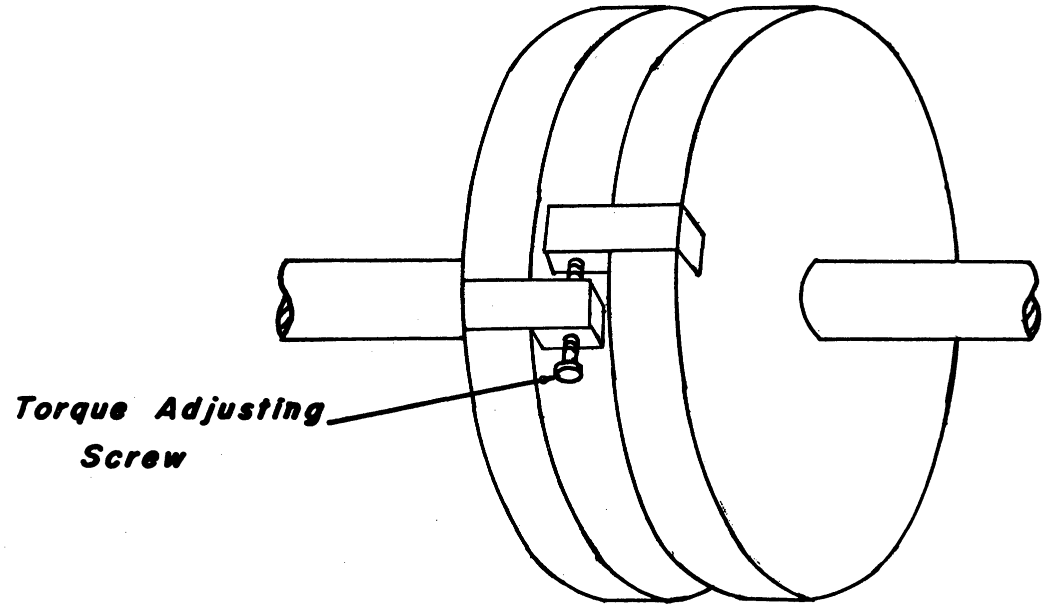


Fig. 4. Torque Adjustment

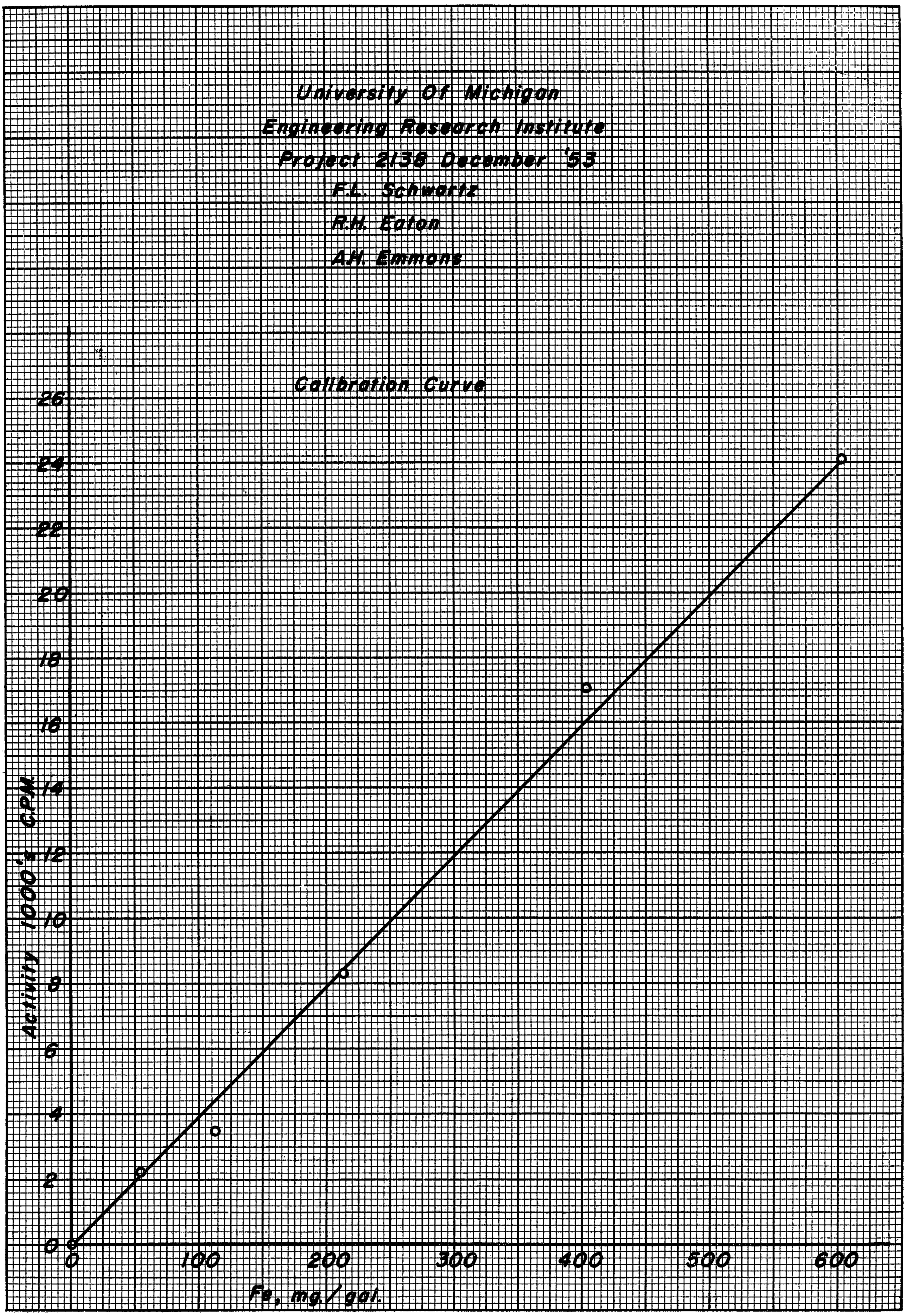


Fig. 5. Calibration Curve

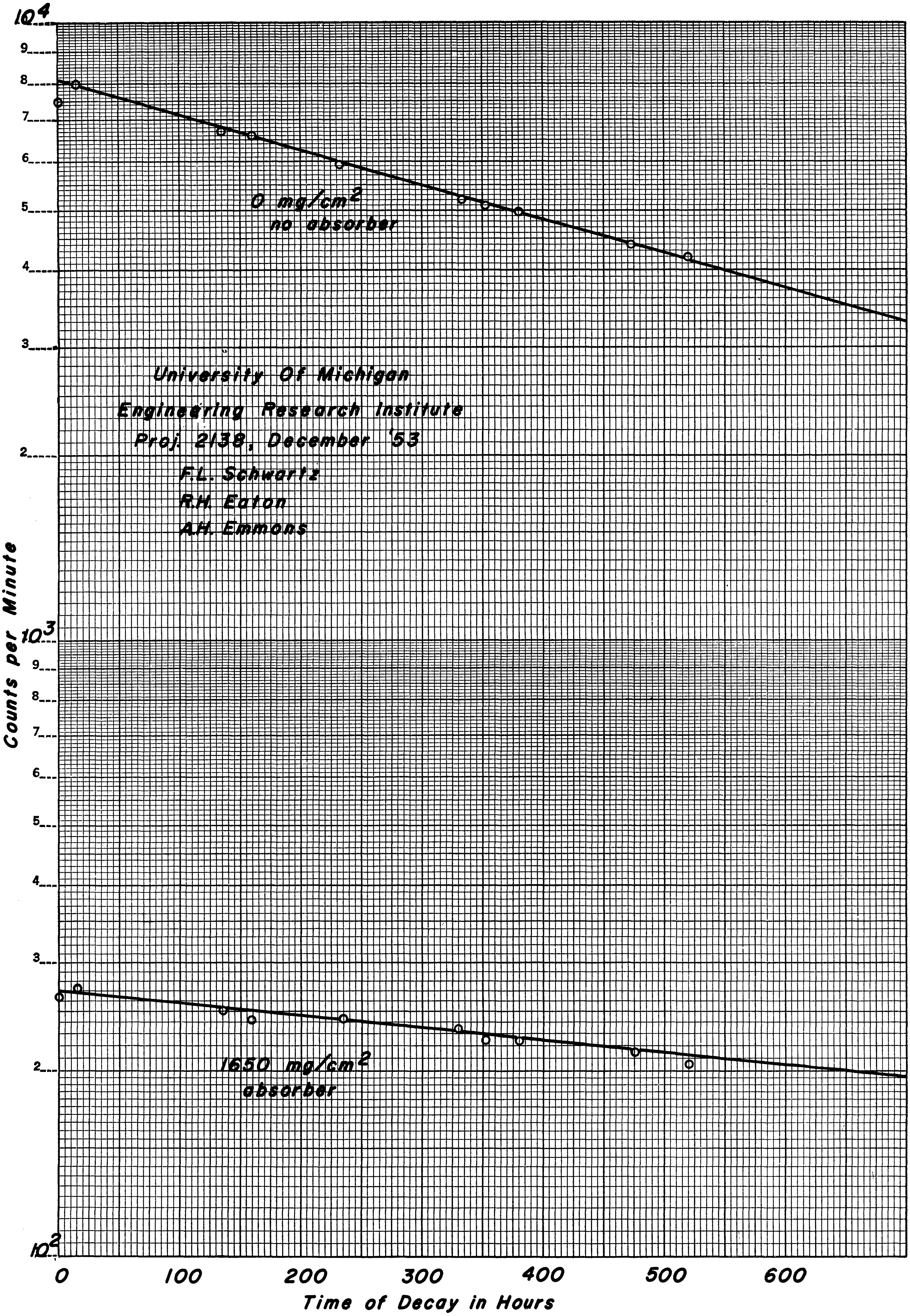


Fig. 6. Decay Chart

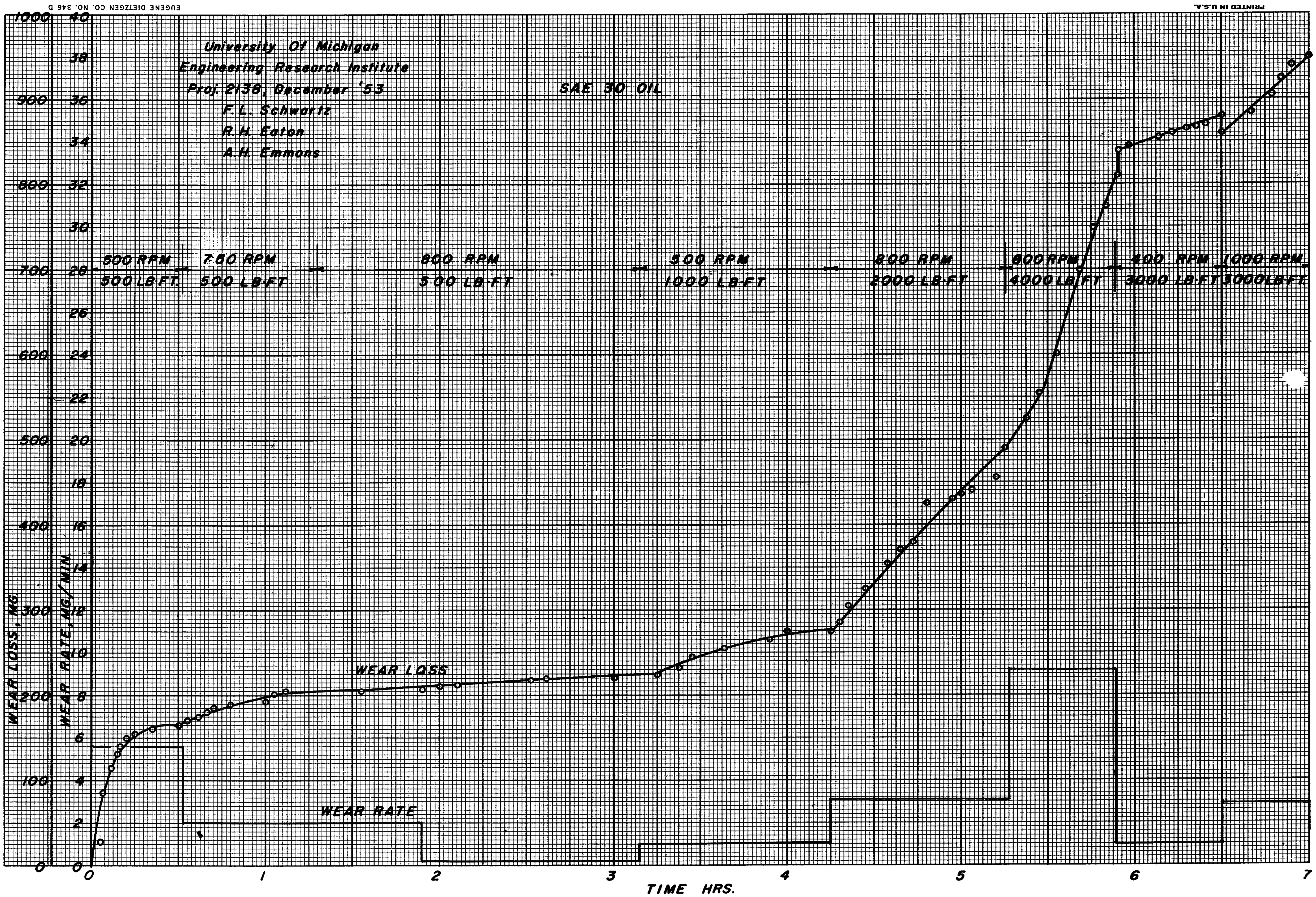


Fig. 7. Wear Data, SAE 30 Mineral Oil

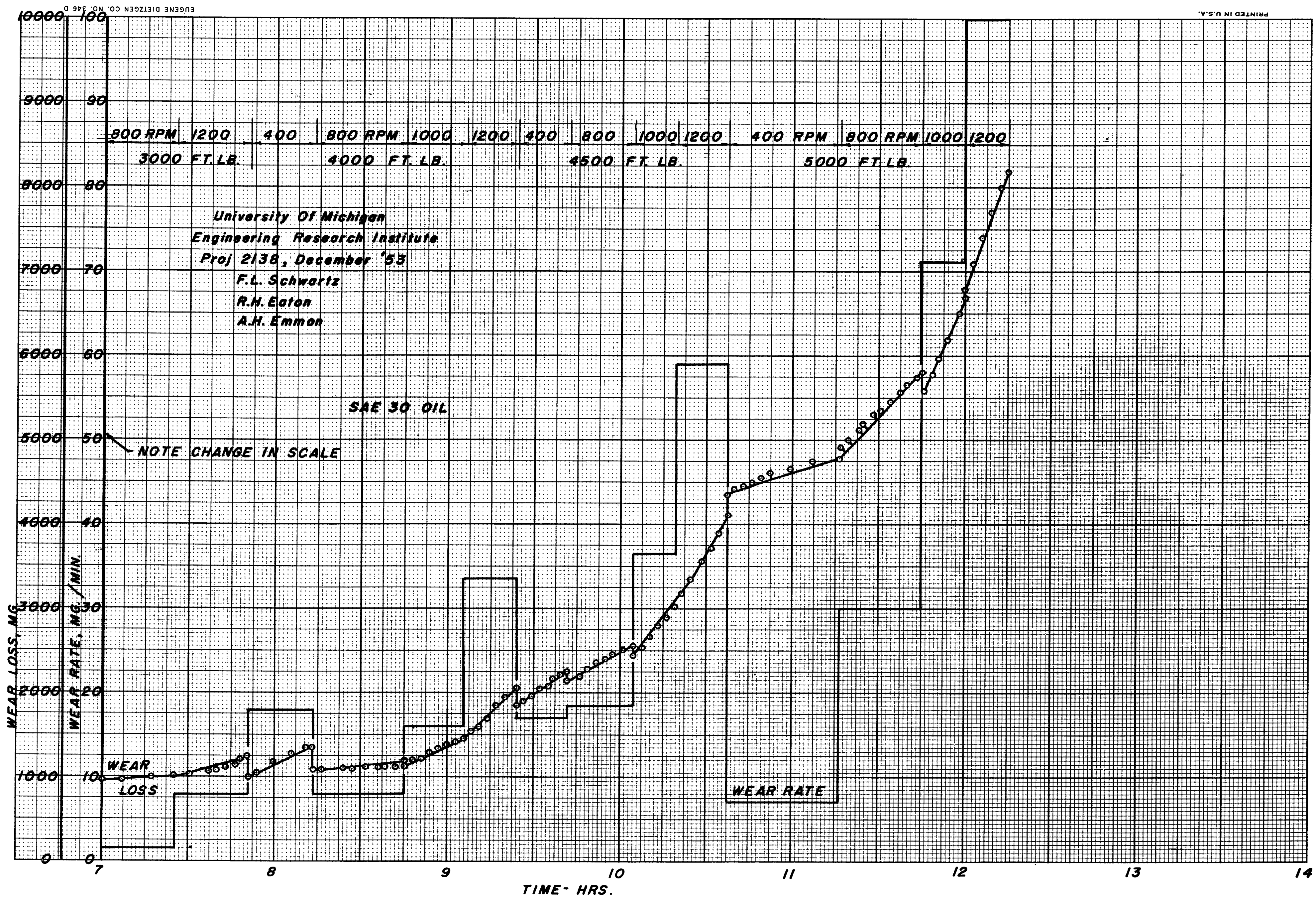


Fig. 8. Wear Data, SAE 30 Mineral Oil

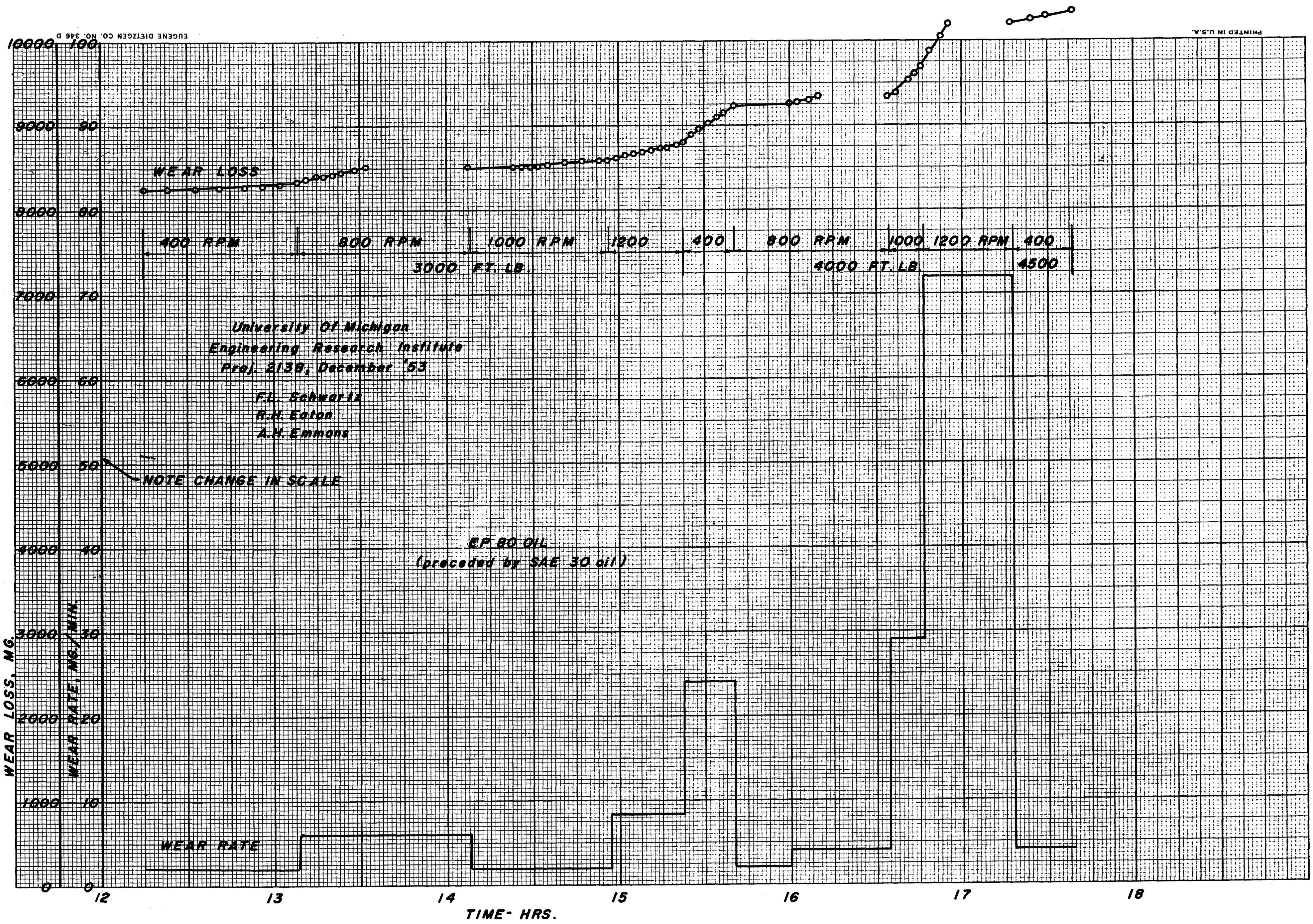


Fig. 9. Wear Data, Worn Gear, EP-80 Gear Lubricant

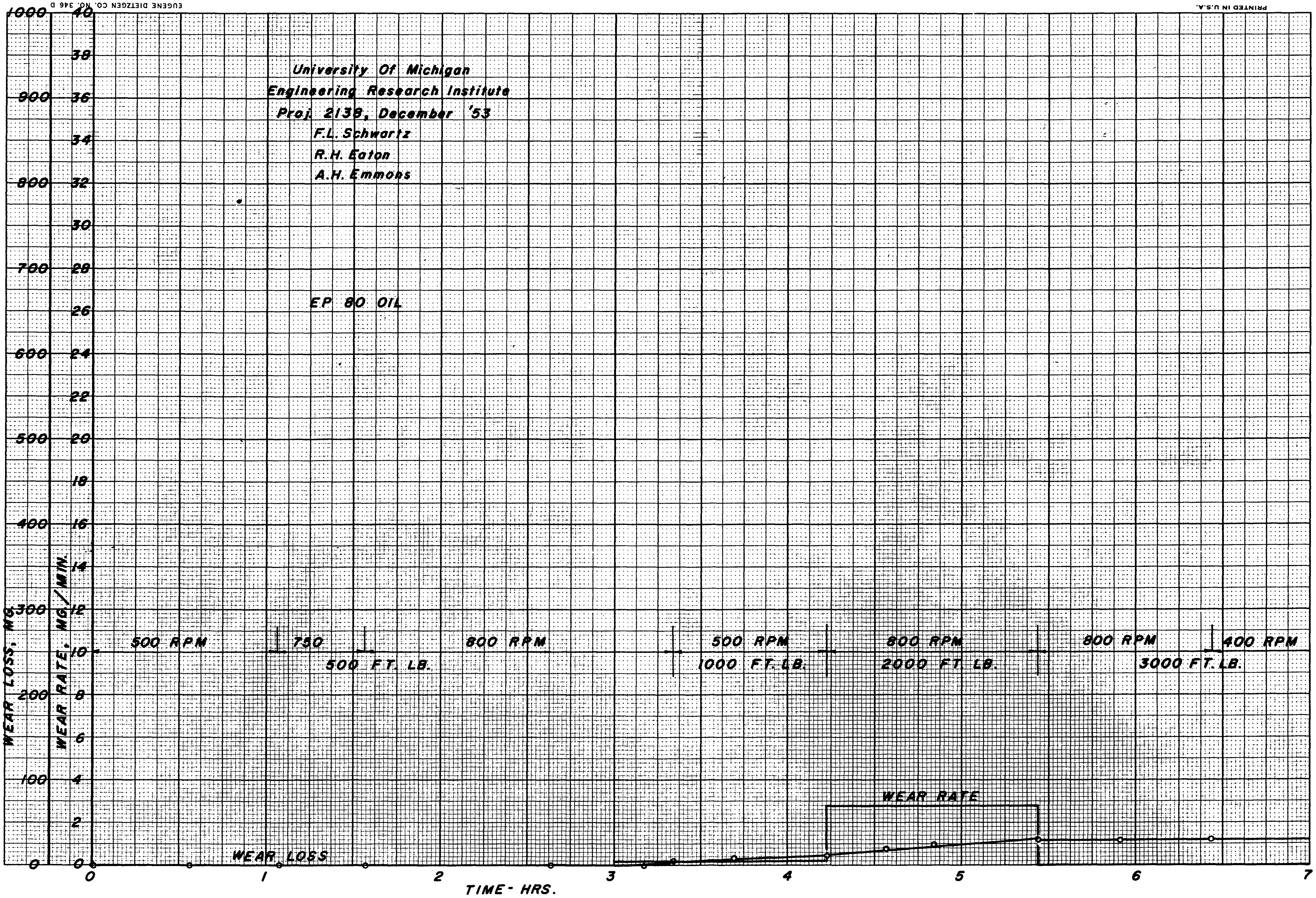


Fig. 10. Wear Data, EP-80 Gear Lubricant

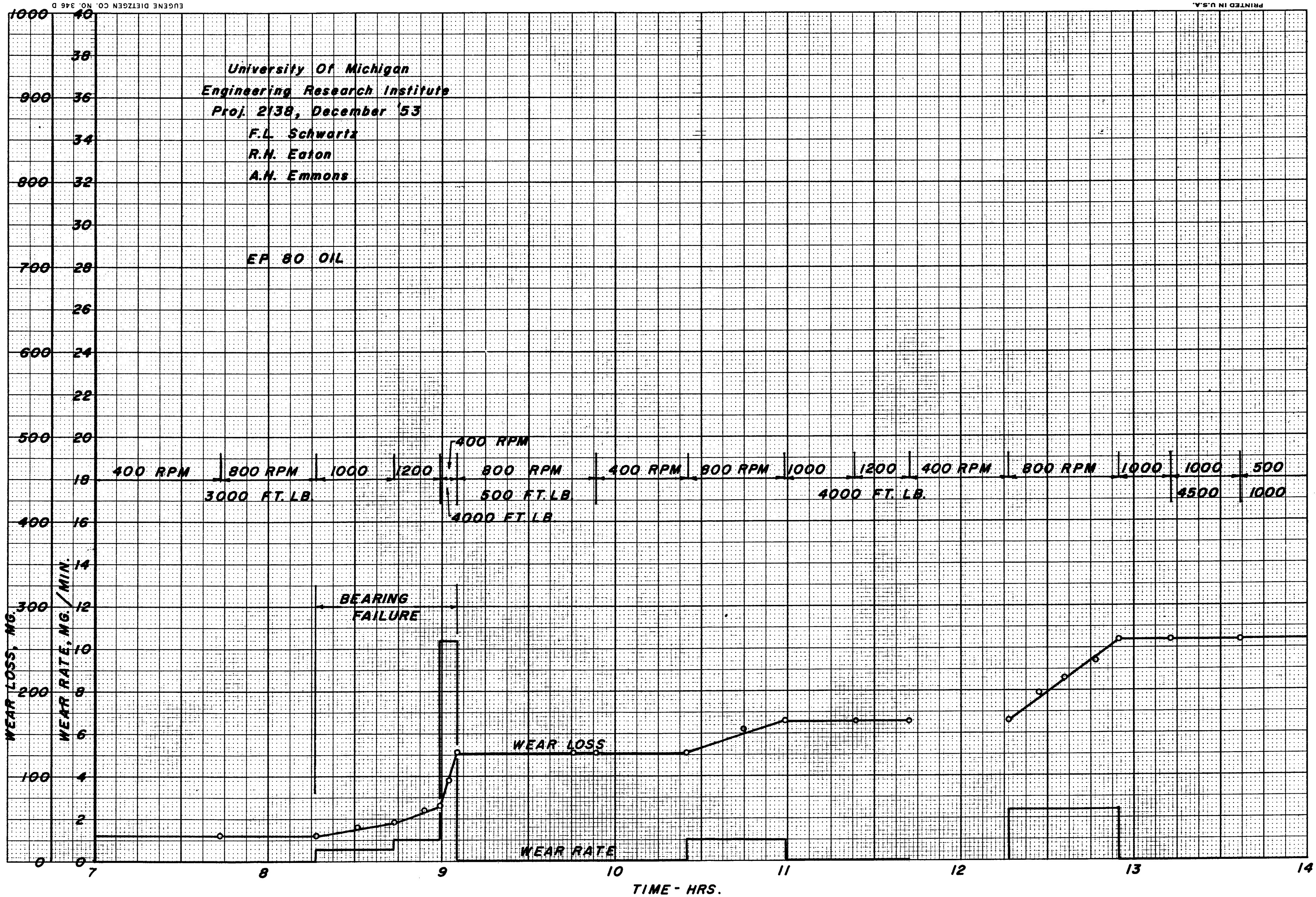


Fig. 11. Wear Data, EP-80 Gear Lubricant

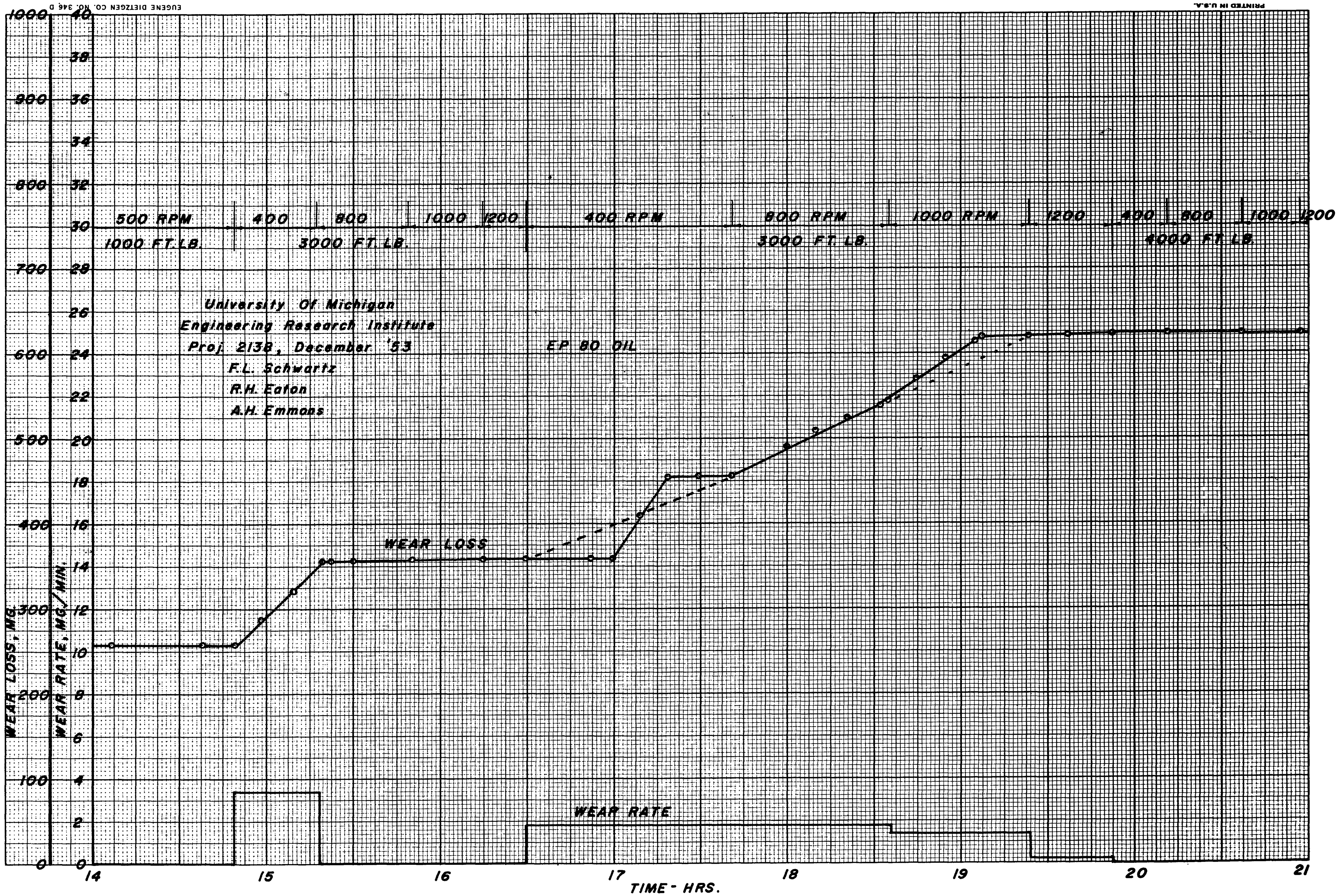


Fig. 12. Wear Data, EP-80 Gear Lubricant

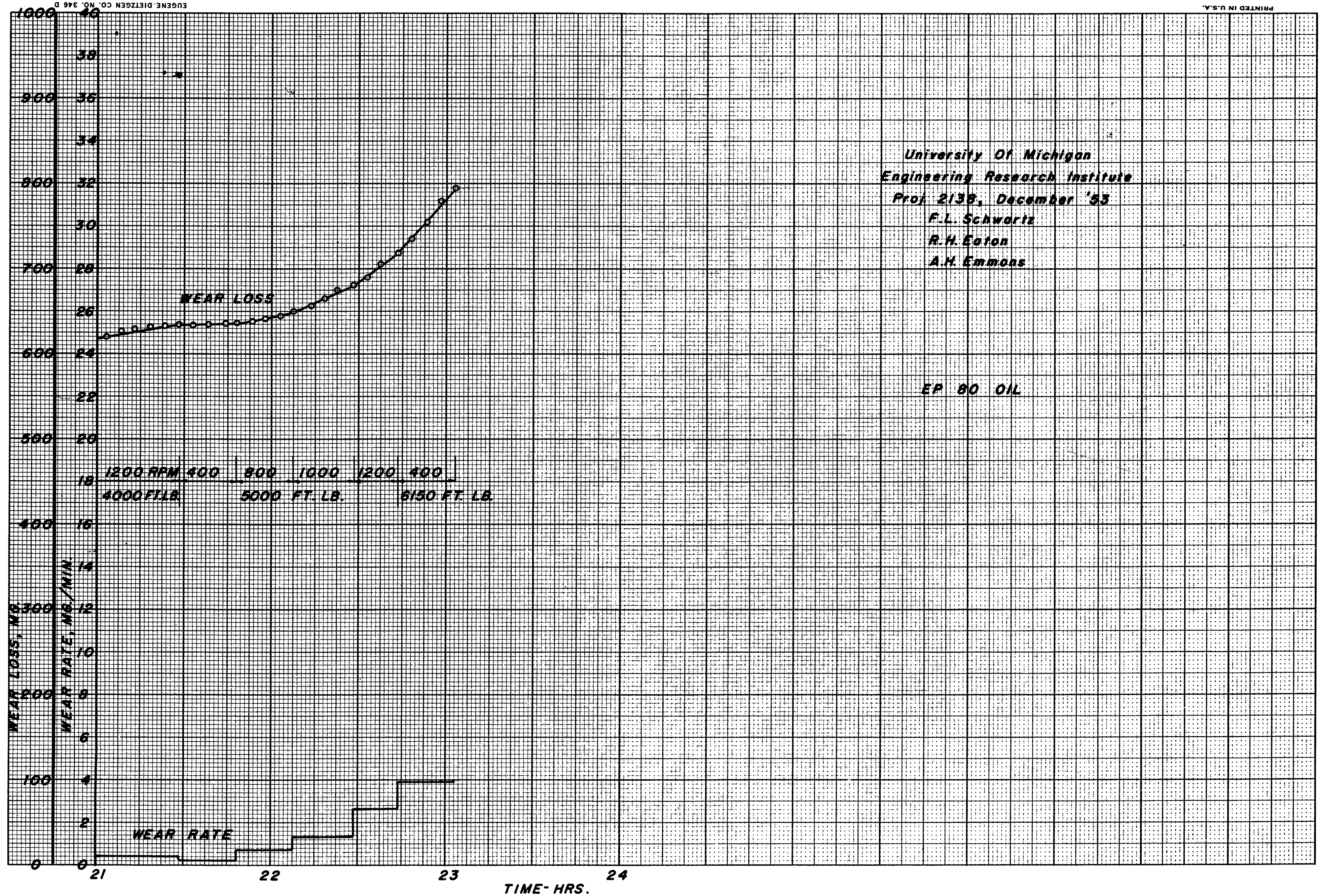


Fig. 13. Wear Data, EP-80 Gear Lubricant

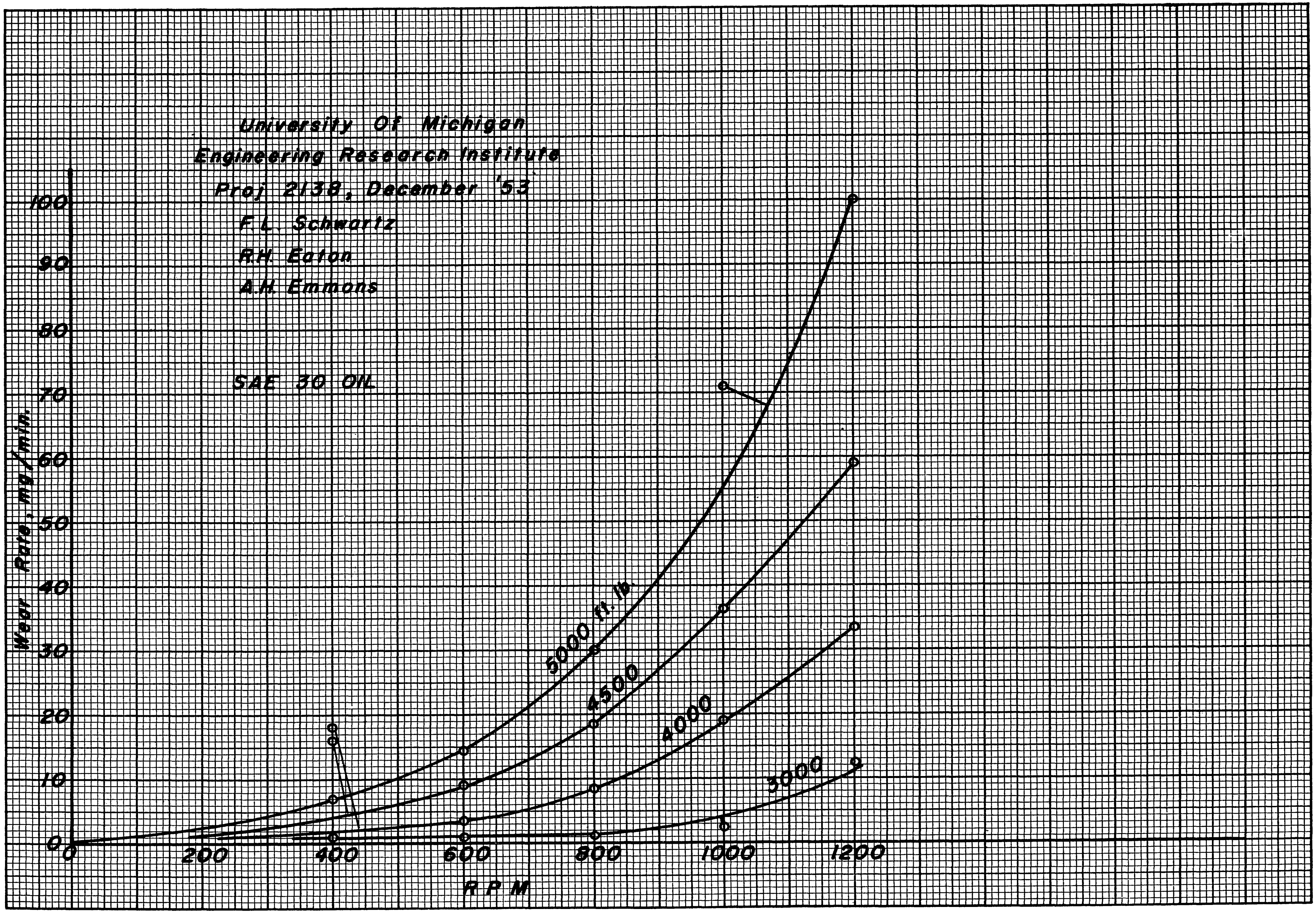


Fig. 14. Wear Rate vs RPM, SAE 30 Oil

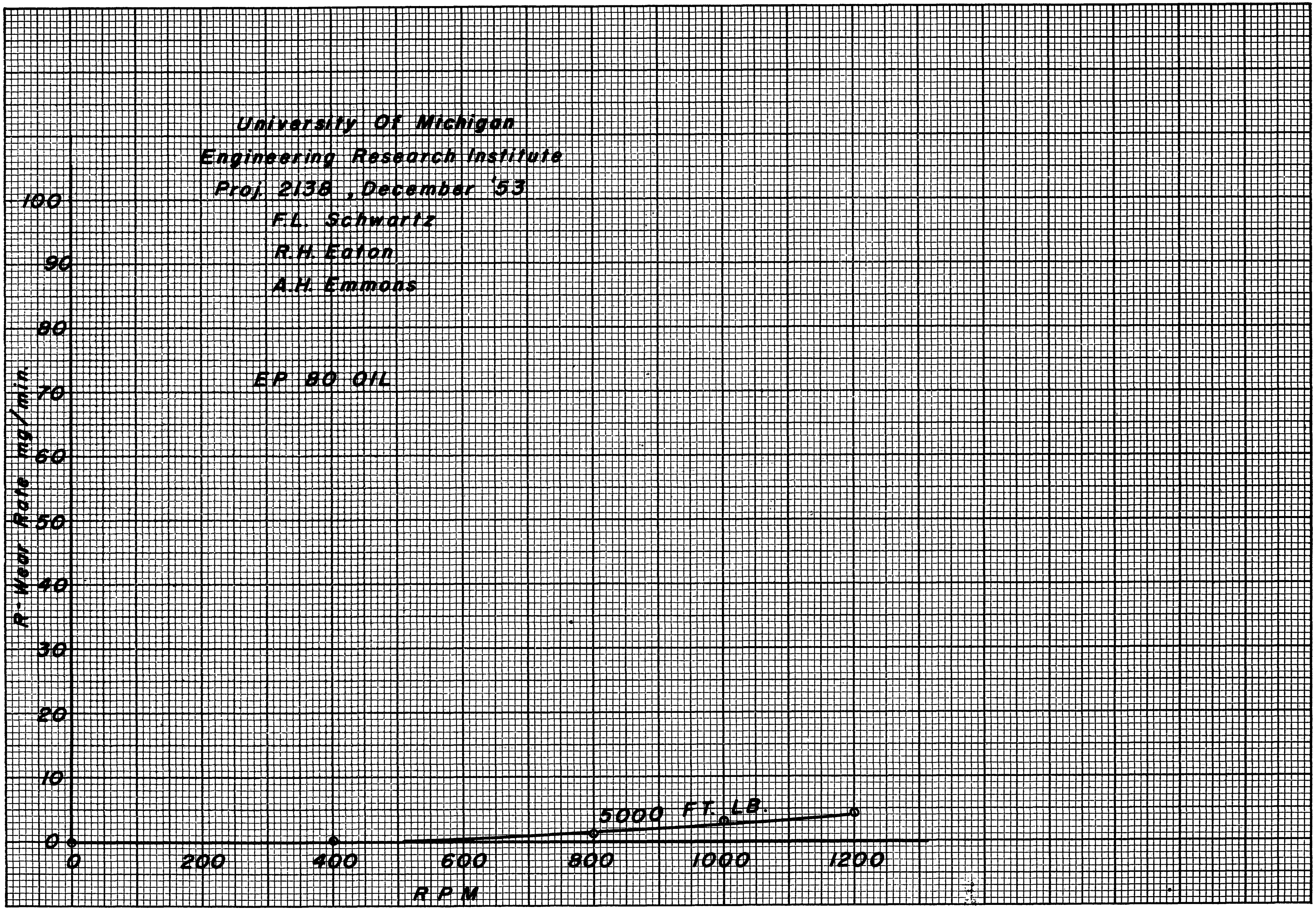


Fig. 15. Wear Rate vs RPM, EP-80 Oil

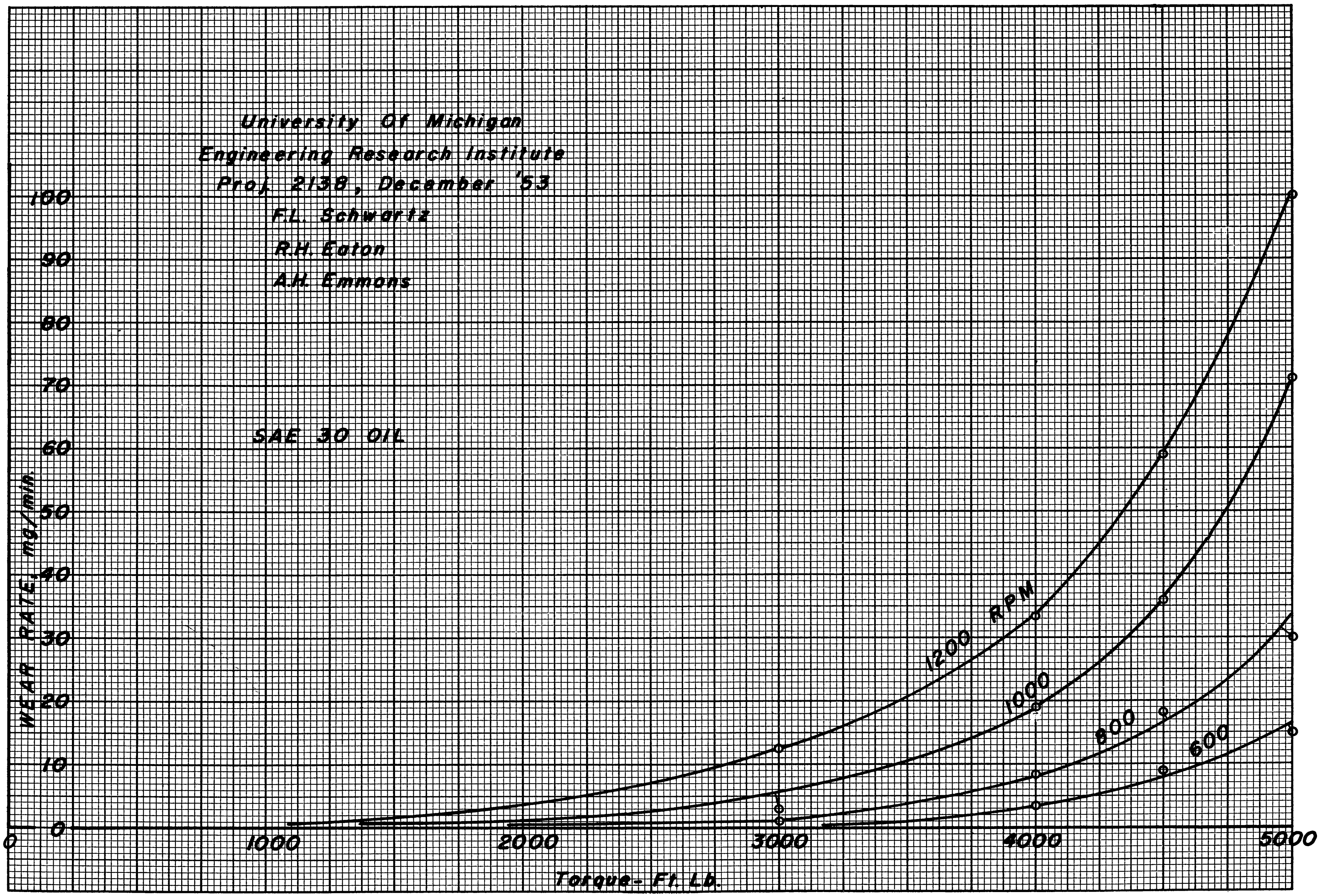


Fig. 16. Wear Rate vs Torque, SAE 30 Oil

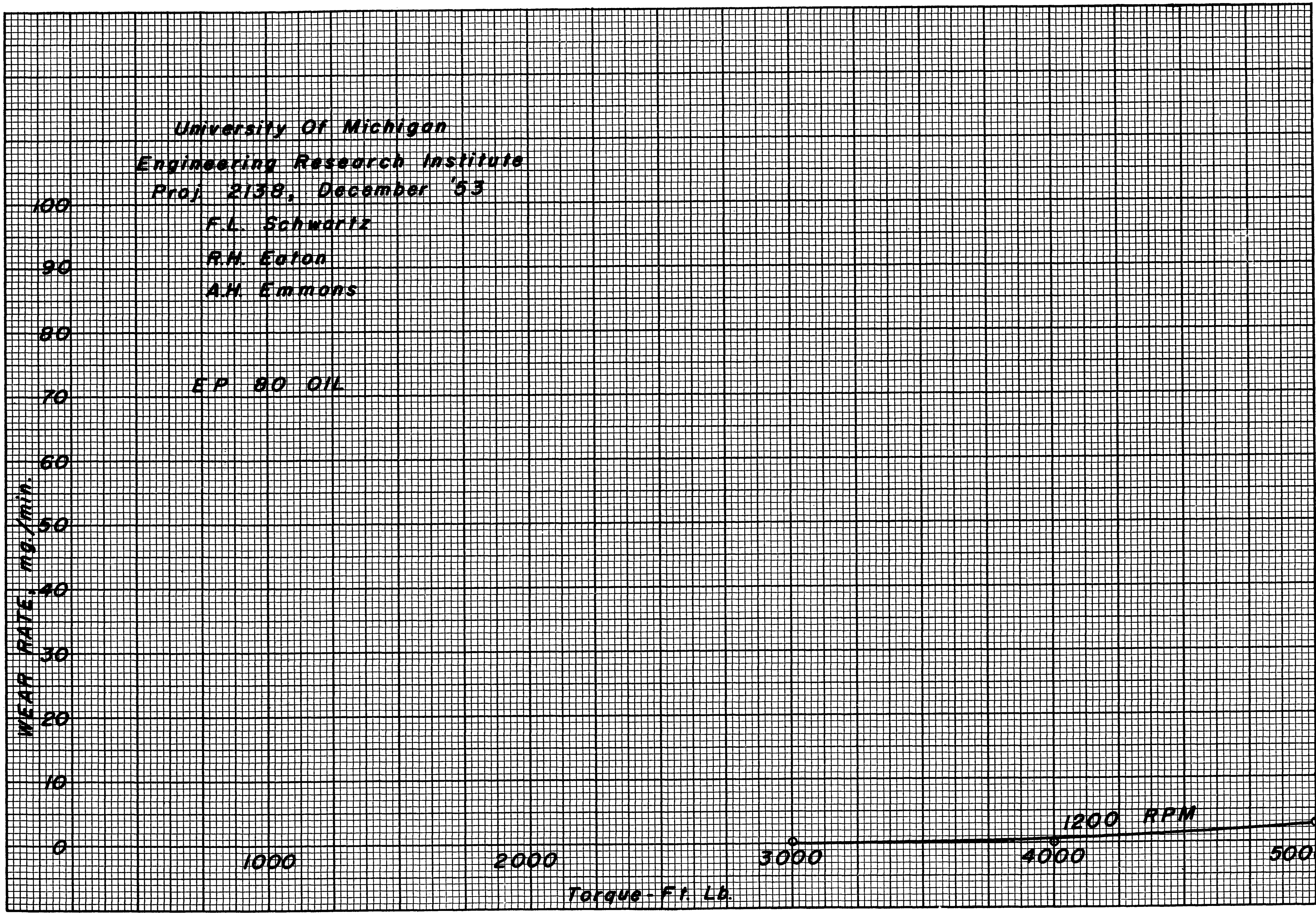


Fig. 17. Wear Rate vs Torque, EP-80 Oil

DISCUSSION OF PHOTOGRAPHS

The calibration particles are shown, magnified 110 times, in Fig. 18. The grinding process generated enough heat to cause some of the particles to melt and reform into tiny spheres. The largest particles have an average dimension of 0.002 inch.

The calibration oil system is shown in Fig. 19 with the lead shields removed to show the various parts. The rate meter and recording ammeter used in this research are shown in Fig. 20. The oil system used in the full scale testing is shown in Fig. 21 with the lead shielding surrounding the small counting chamber. The overall test set-up is shown in Fig. 22 and a close-up of the four-square arrangement in Fig. 23.

The strip chart shown in Fig. 24 contains a record of the background count taken prior to the test and the data taken during the first few minutes of testing. The rapid initial wear caused the recording meter to go off scale requiring a change to a higher scale. The strip chart shown in Fig. 25 was included to show typical data taken during the test. The change in slope under different conditions is easily seen in this photograph.

The tooth shown in Fig. 26 was broken from the radioactive sun gear. The surface shown in the photograph was the result of about ten hours running with SAE 30 mineral oil. The photograph of Fig. 27 is the opposite side of the same tooth after twenty hours running time using EP-80 gear lubricant with an even higher maximum load. This surface was not badly worn or pitted. Most of the damage to this surface was caused by the failure of the planet shaft bearing.

The planet gear shown in Fig. 28 ran with the sun gear tooth shown in Fig. 26. The surface was badly worn. The planet gear shown in Fig. 29 ran with the sun gear tooth shown in Fig. 27 using the EP-80 gear lubricant. This gear still has some of the original tool marks caused by the manufacturing process. The failed planet shaft bearing is shown in Fig. 30 and the planet shaft in Fig. 31. This is a typical planet bearing failure with the failure starting in the planet shaft bearing radius.

The radiographs shown in Fig. 32 show a great amount of metal transfer when using SAE 30 mineral oil and very little metal transfer when using EP 80 gear lubricant. The light areas in the radiographs are caused by the radioactive metal which has been transferred from the active gear. The prevention of metal transfer is one of the properties of the EP lubricant which extends gear life.

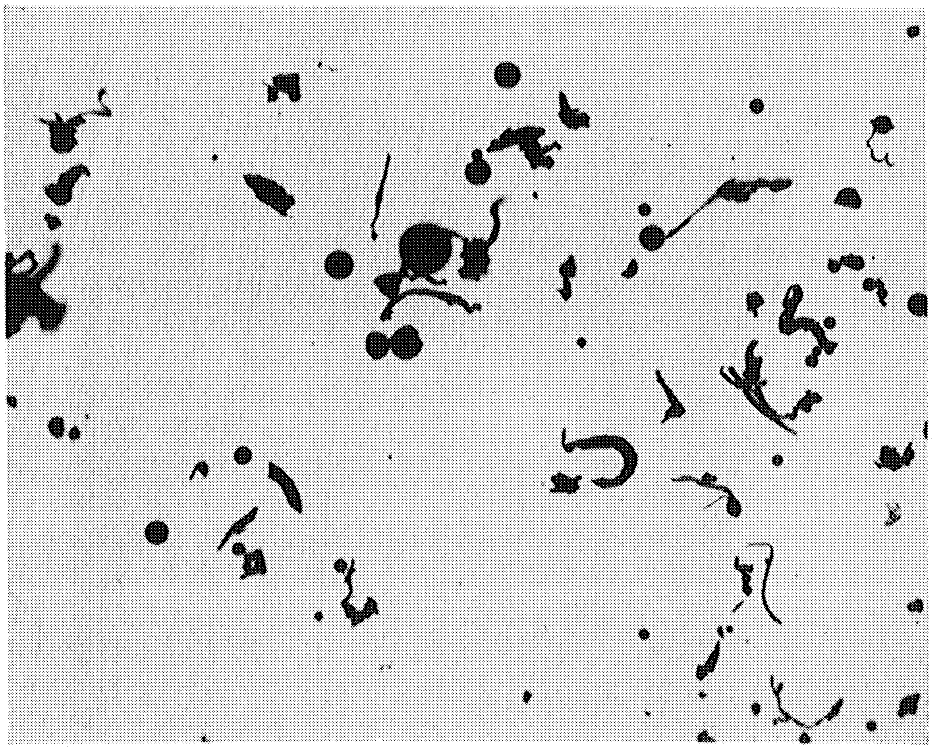


Fig. 18a

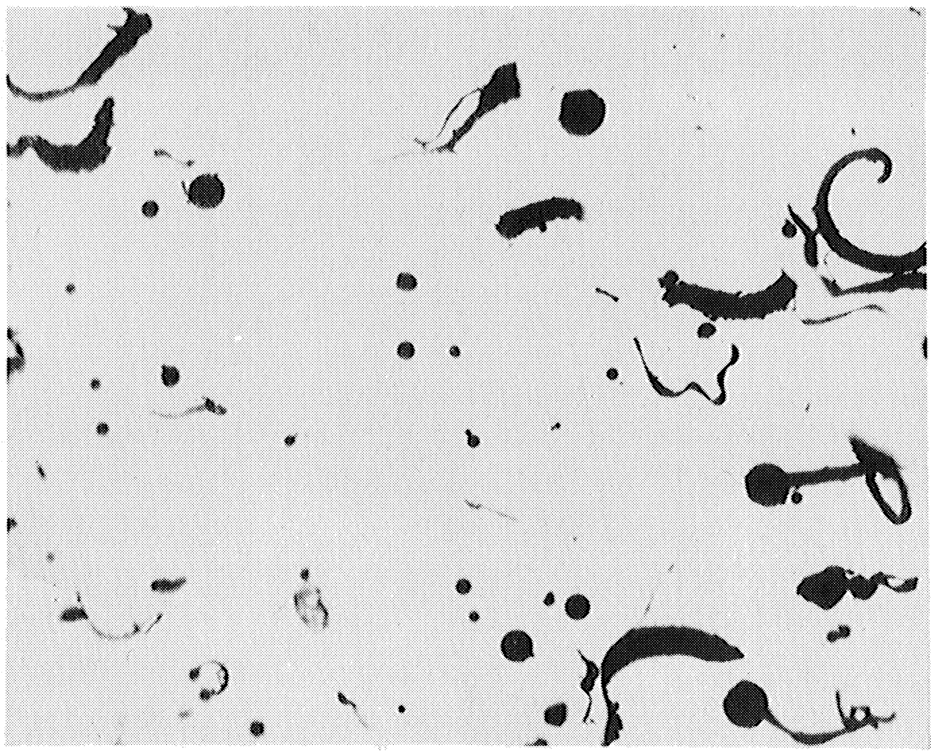


Fig. 18b

Fig. 18. Magnified Calibration Particles

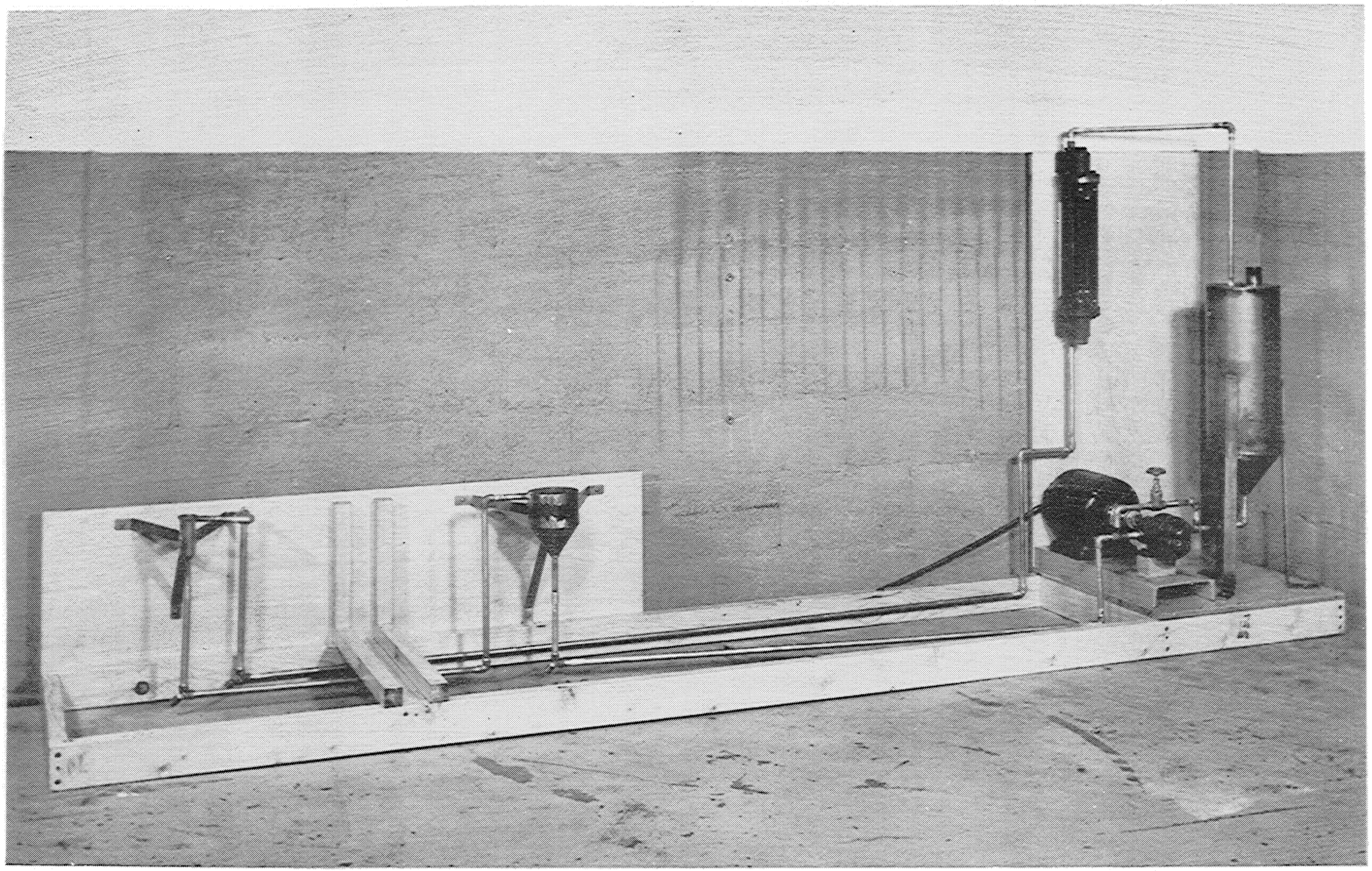


Fig. 19. Calibration System

Fig. 20. Instrumentation

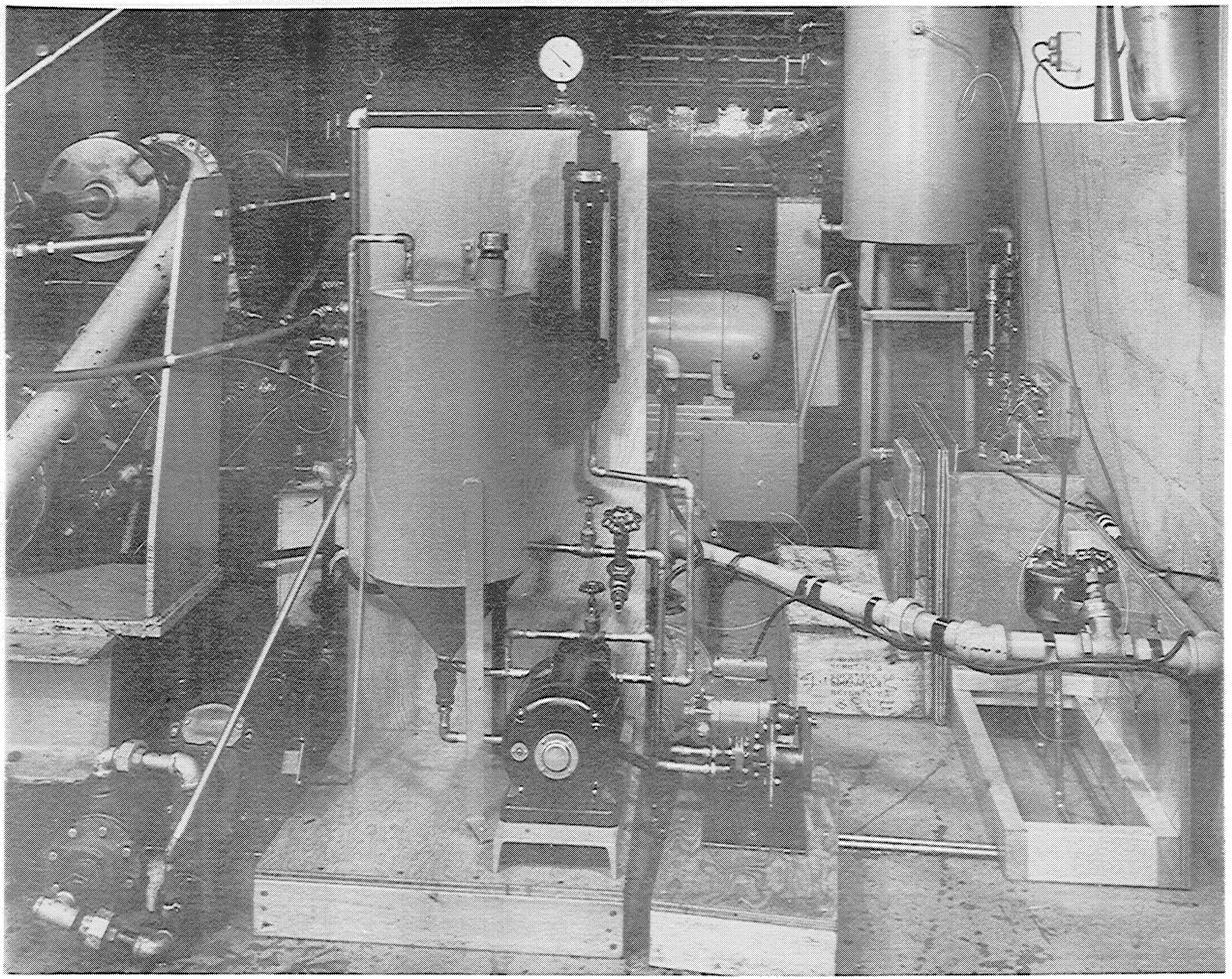


Fig. 21. Test Oil System

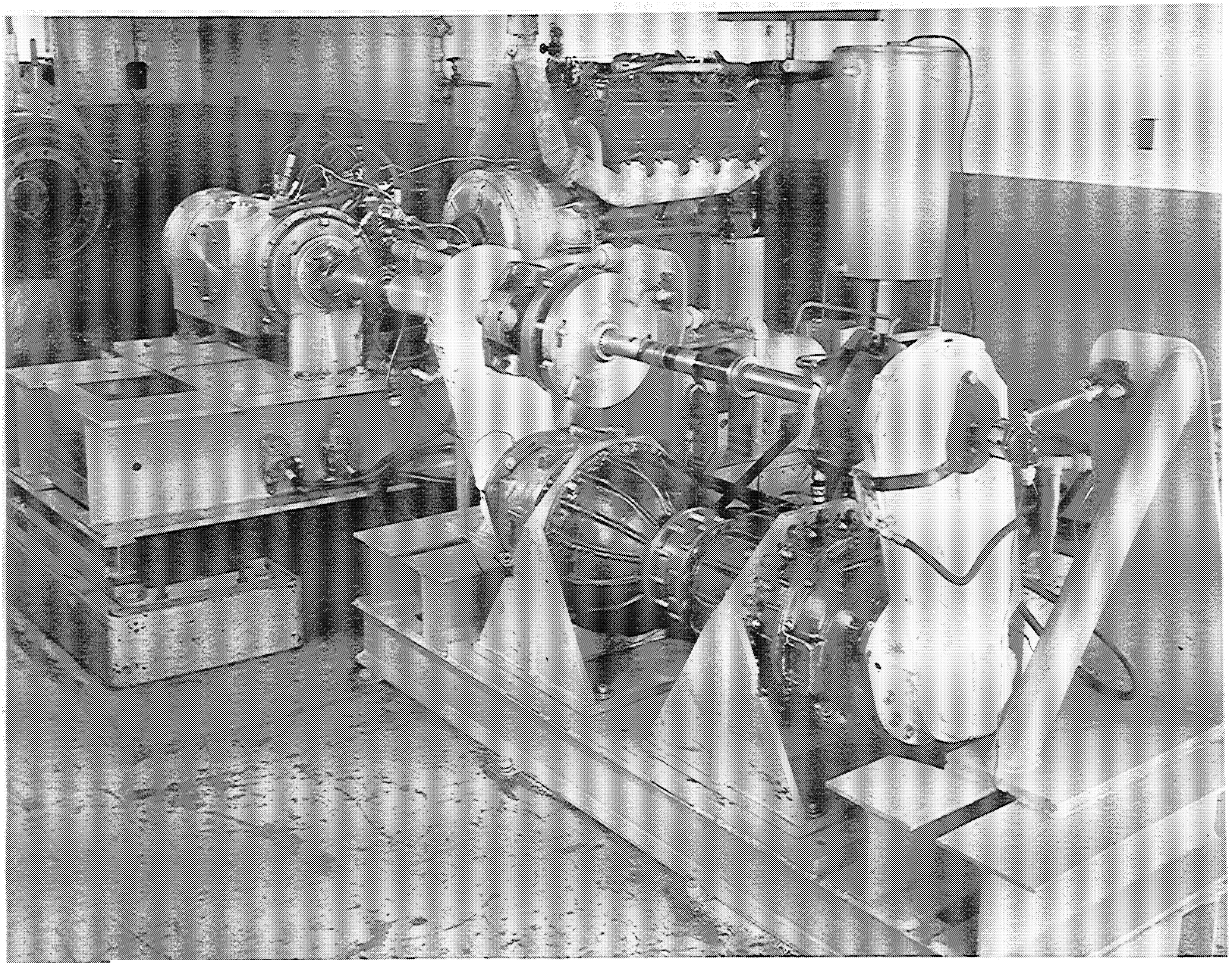


Fig. 22. Overall Test Set Up

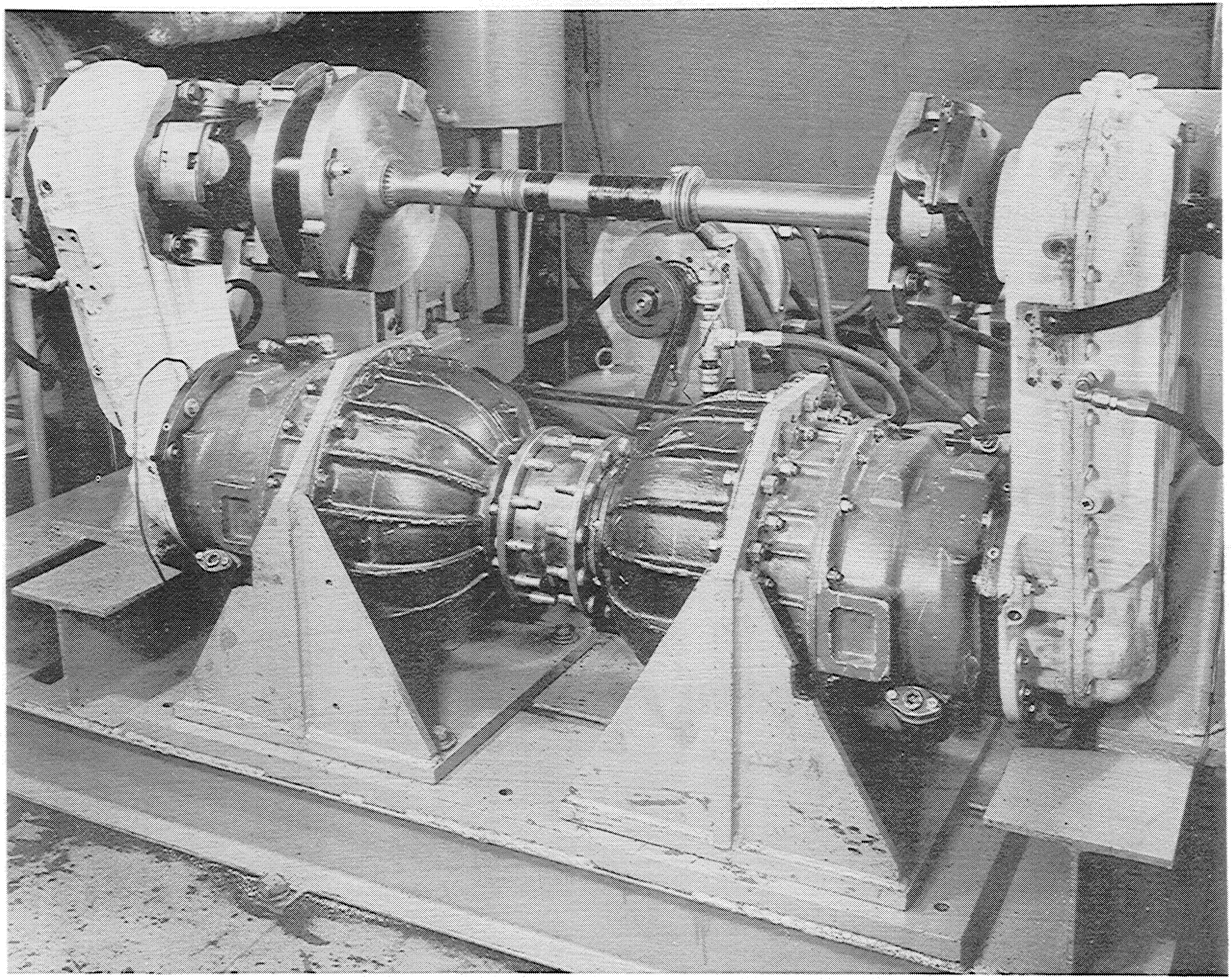


Fig. 23. Four Square Testing Arrangement

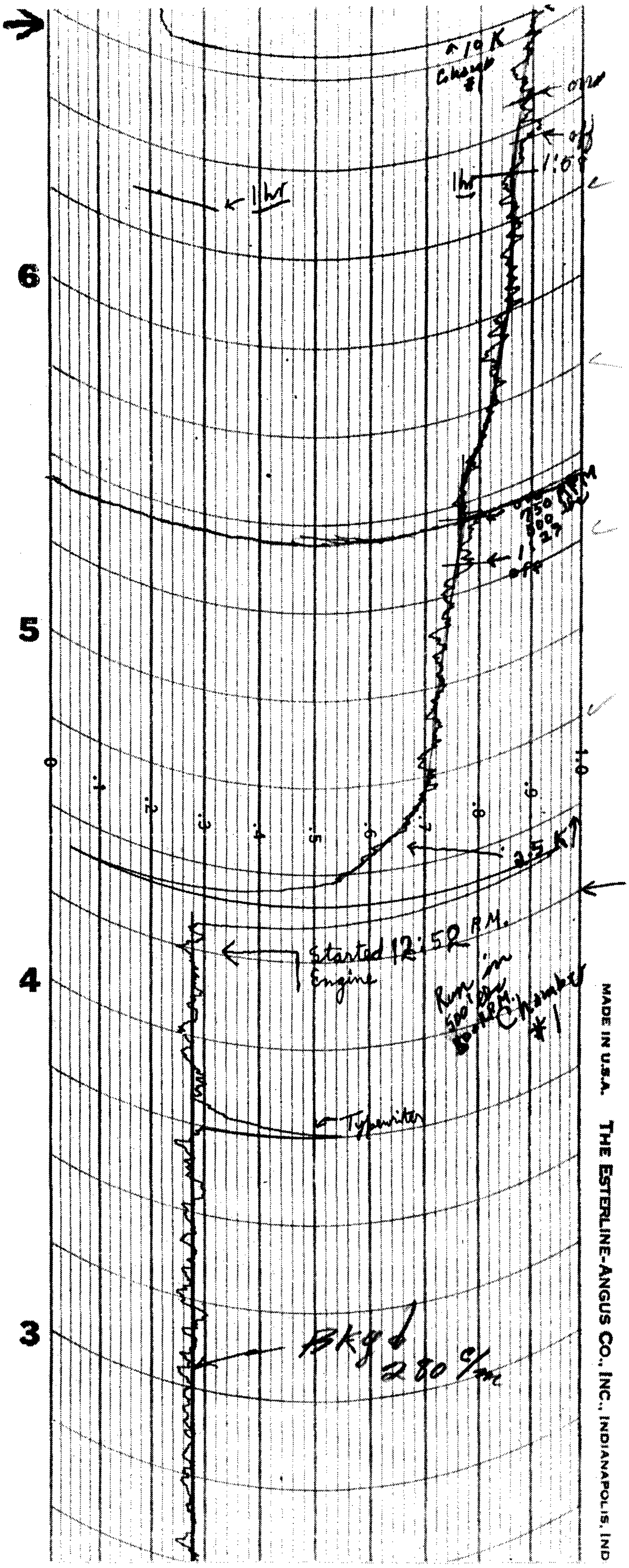


Fig. 24. Strip Chart, Break-in Period

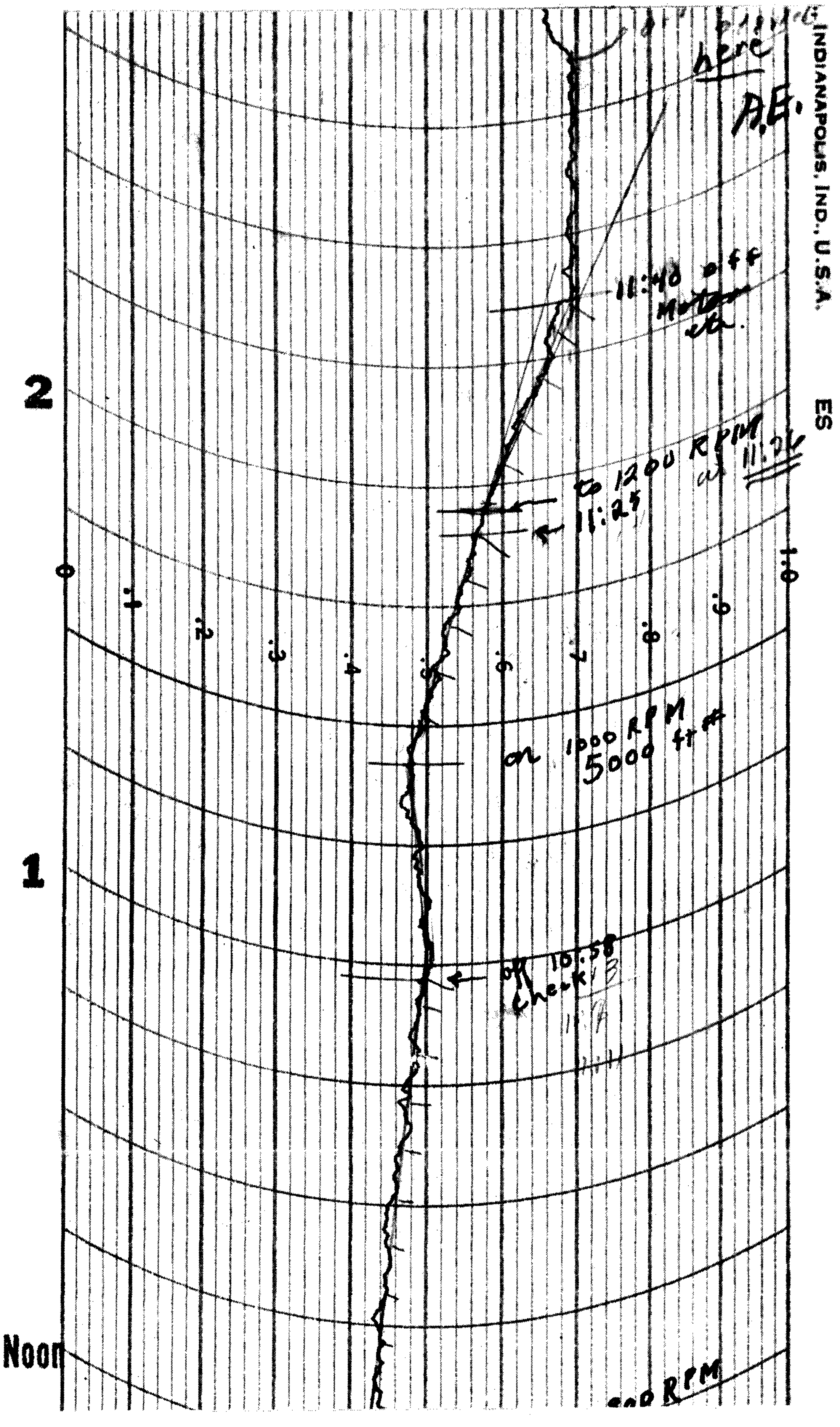


Fig. 25. Strip Chart, Typical Data

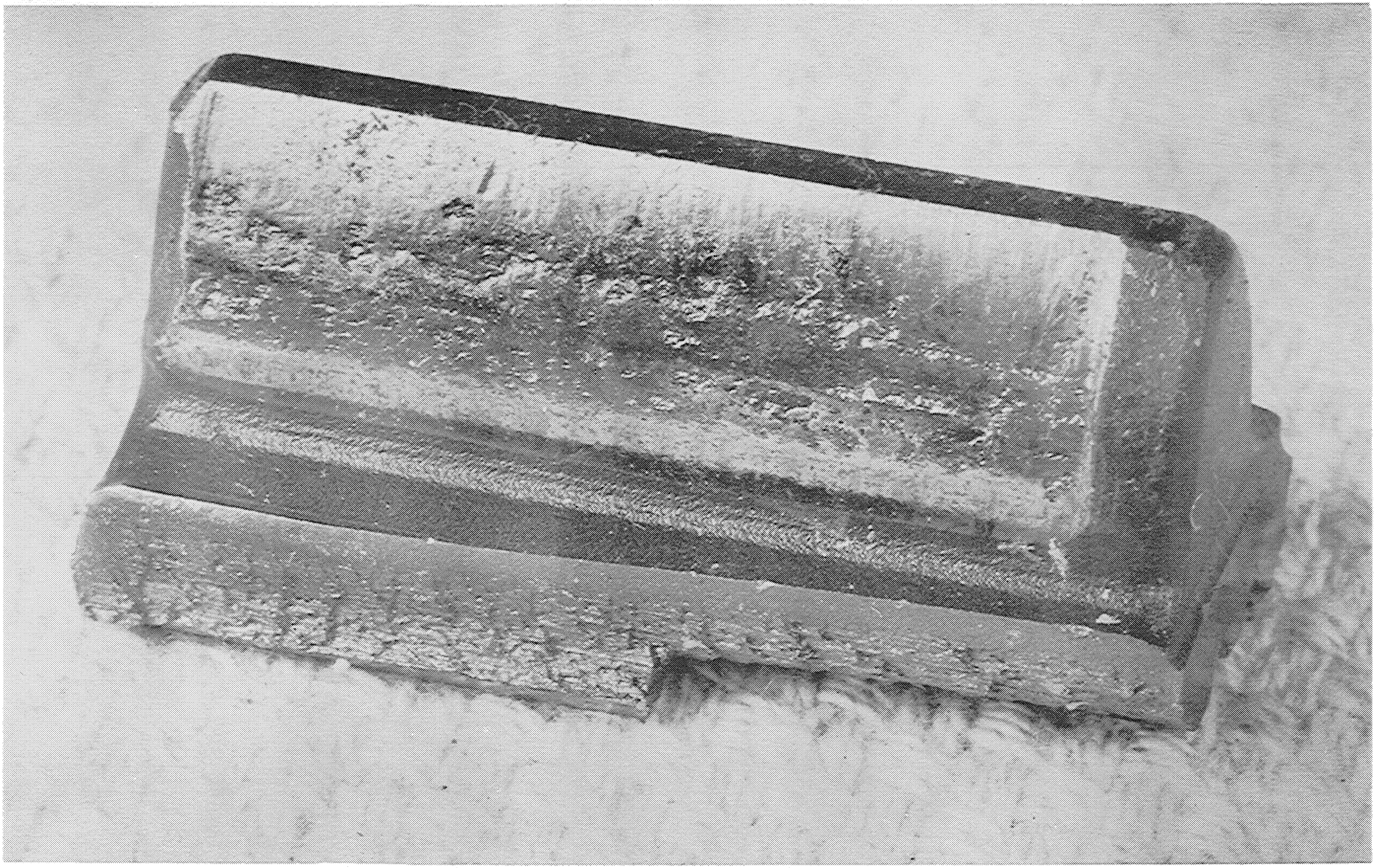


Fig. 26. Radioactive Gear, 10 Hours with SAE 30 Oil

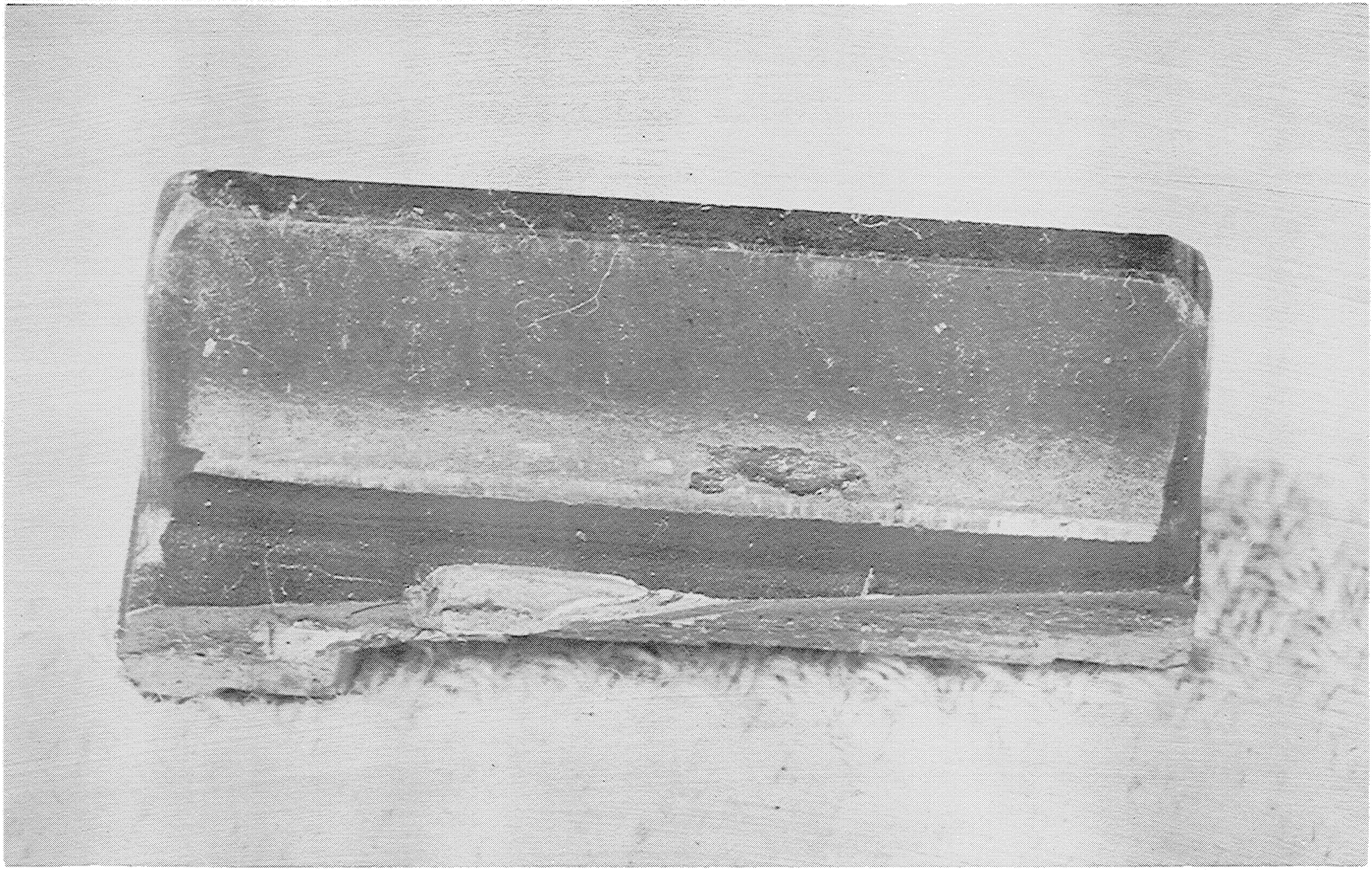


Fig. 27. Radioactive Gear, 20 Hours with EP-80 Oil

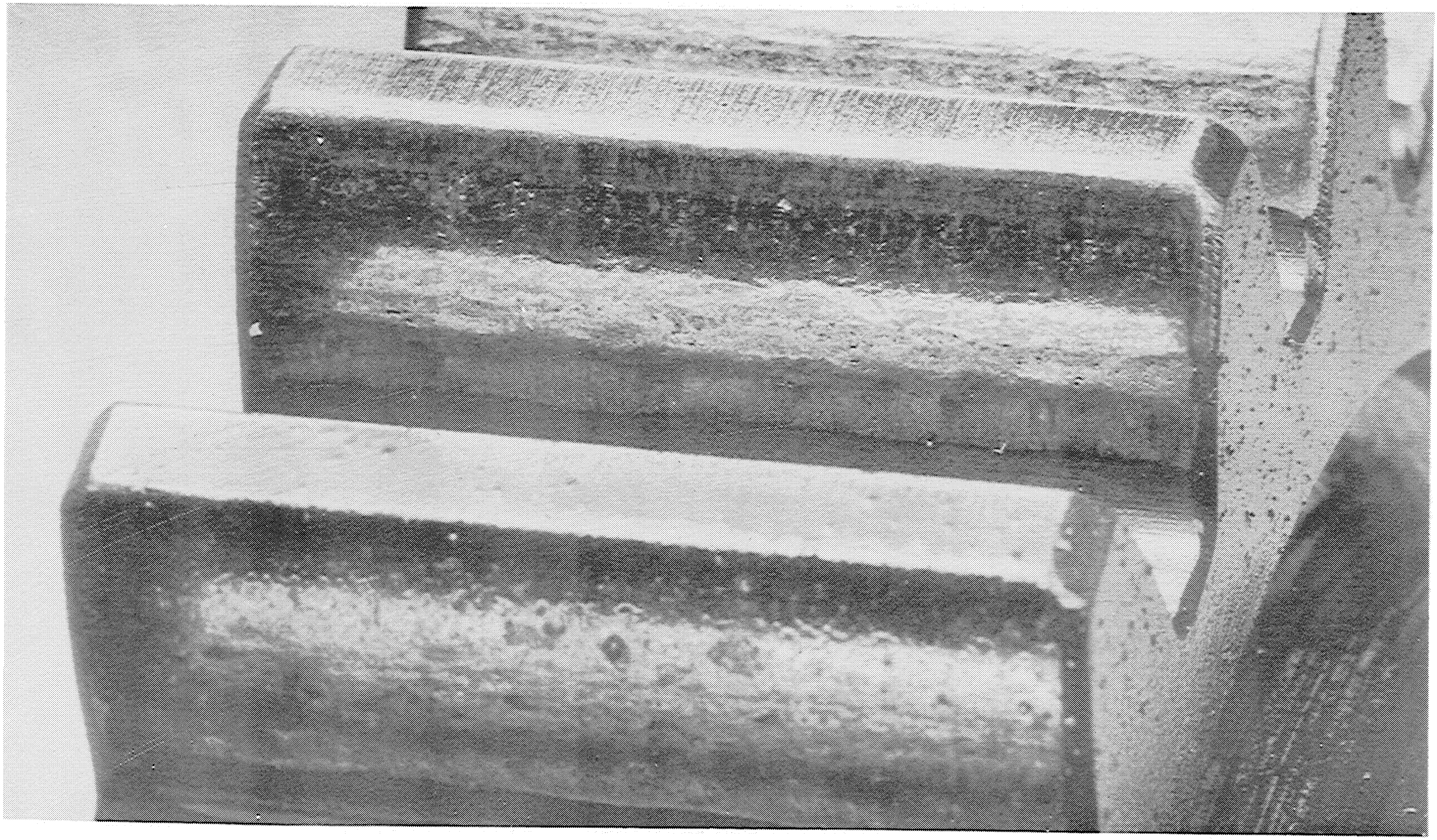


Fig. 28. Planet Gear, 10 Hours with SAE 30 Oil

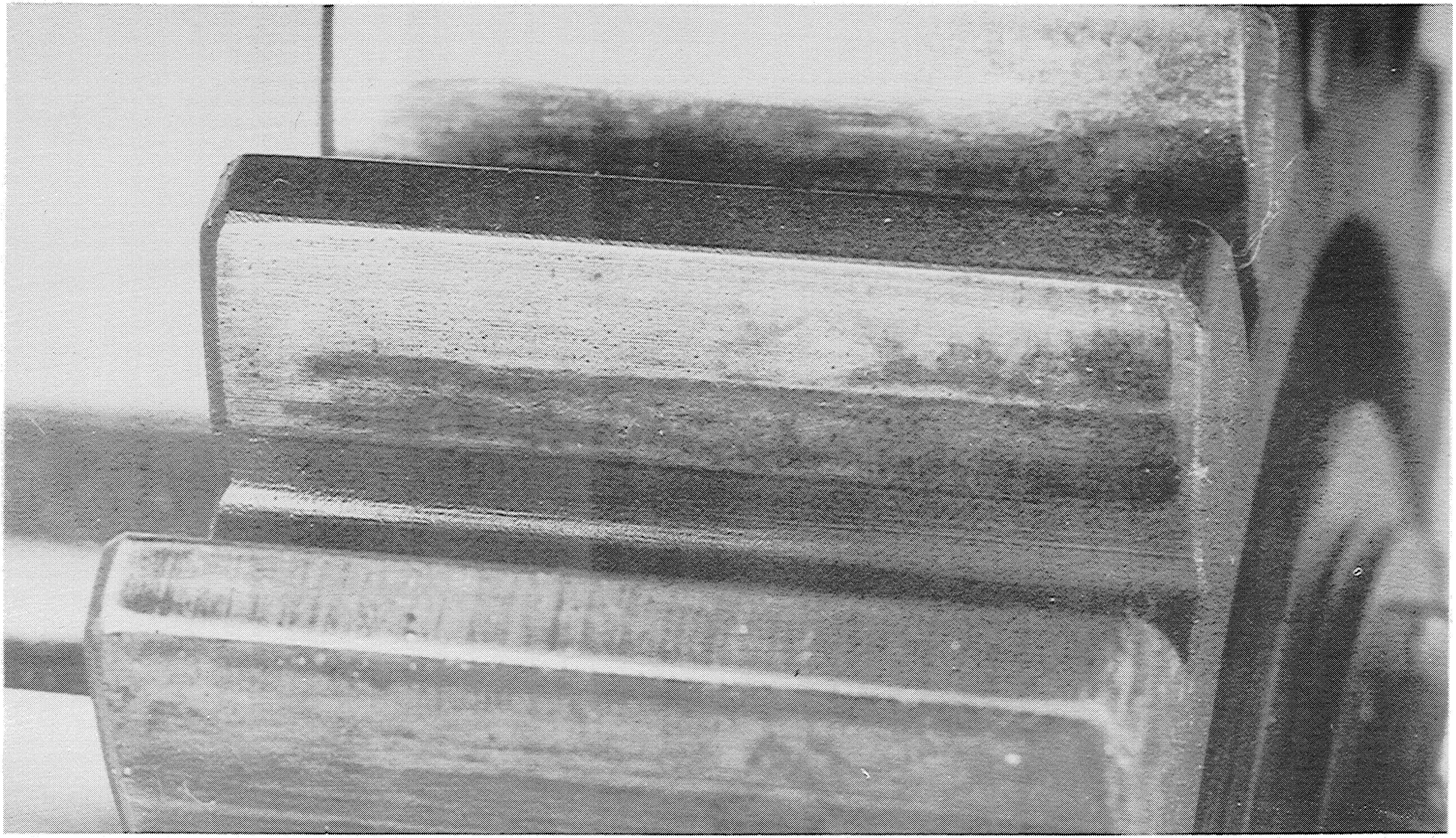


Fig. 29. Planet Gear, 20 Hours with EP-80 Oil

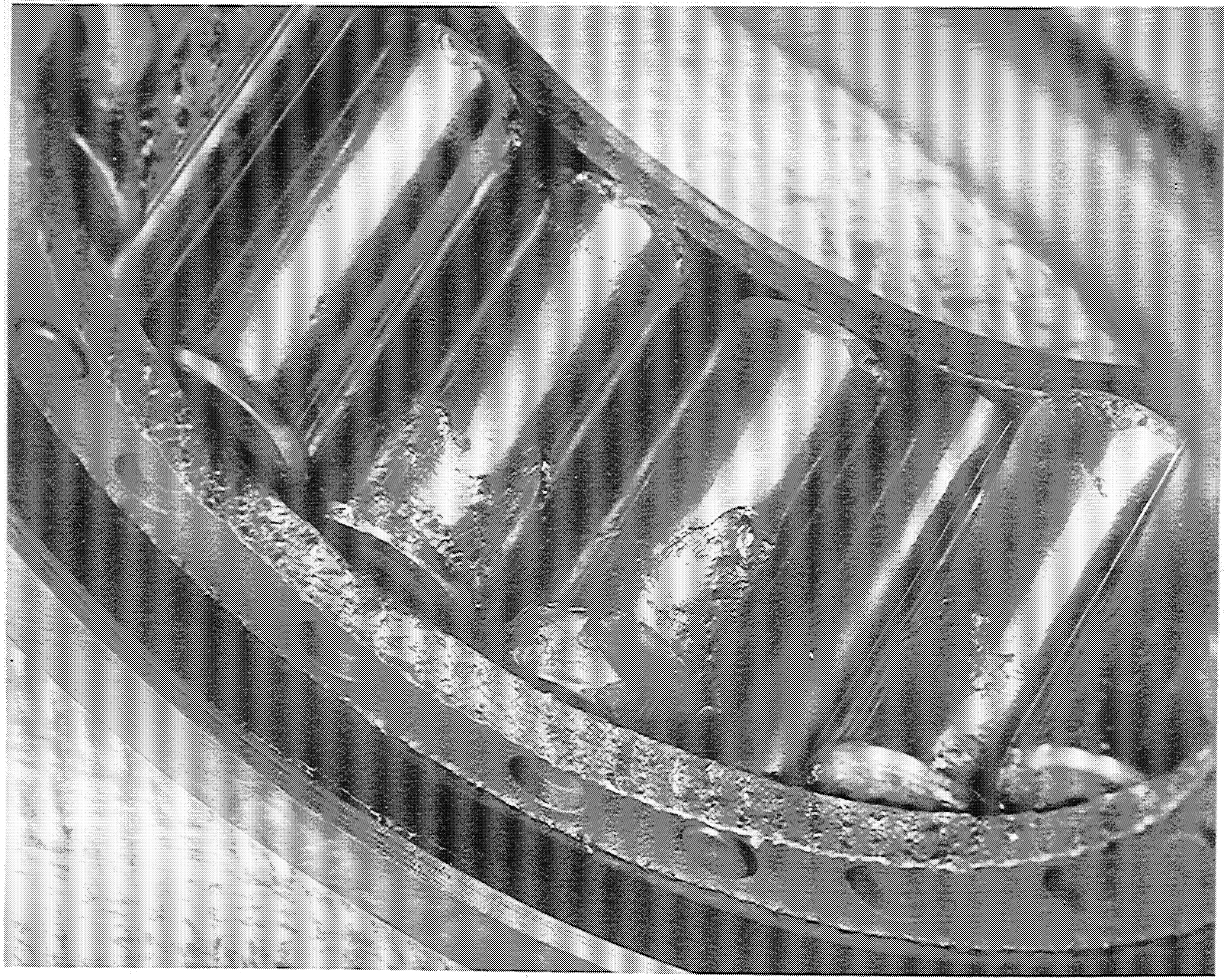


Fig. 30. Failed Planet Shaft Bearing

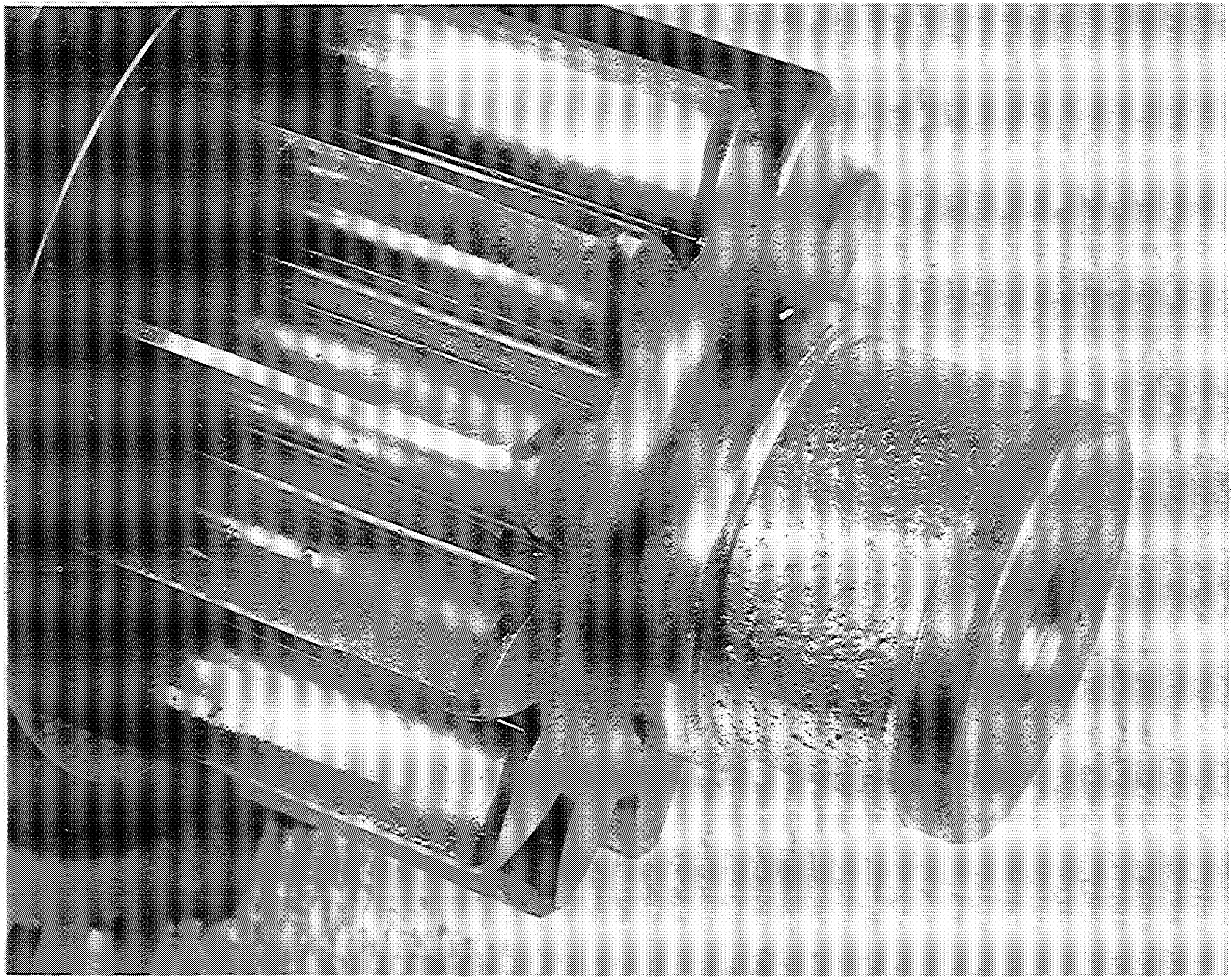
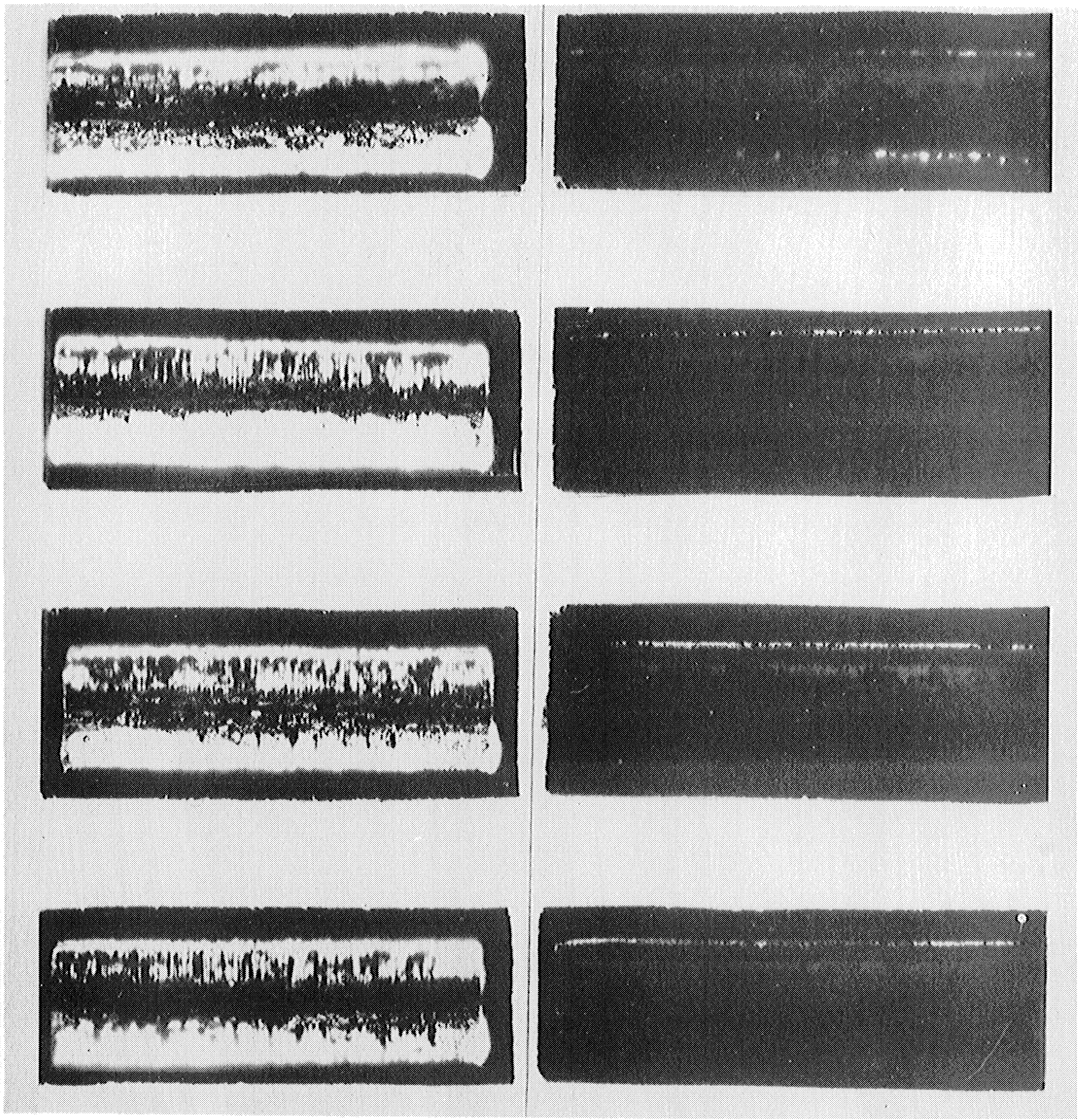


Fig. 31. Failed Planet Shaft



SAE 30 Oil EP-80

Fig. 32. Radiographs of Transferred Metal