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ADVANCES IN WEAR PARTICLE ANALYSIS.(U)
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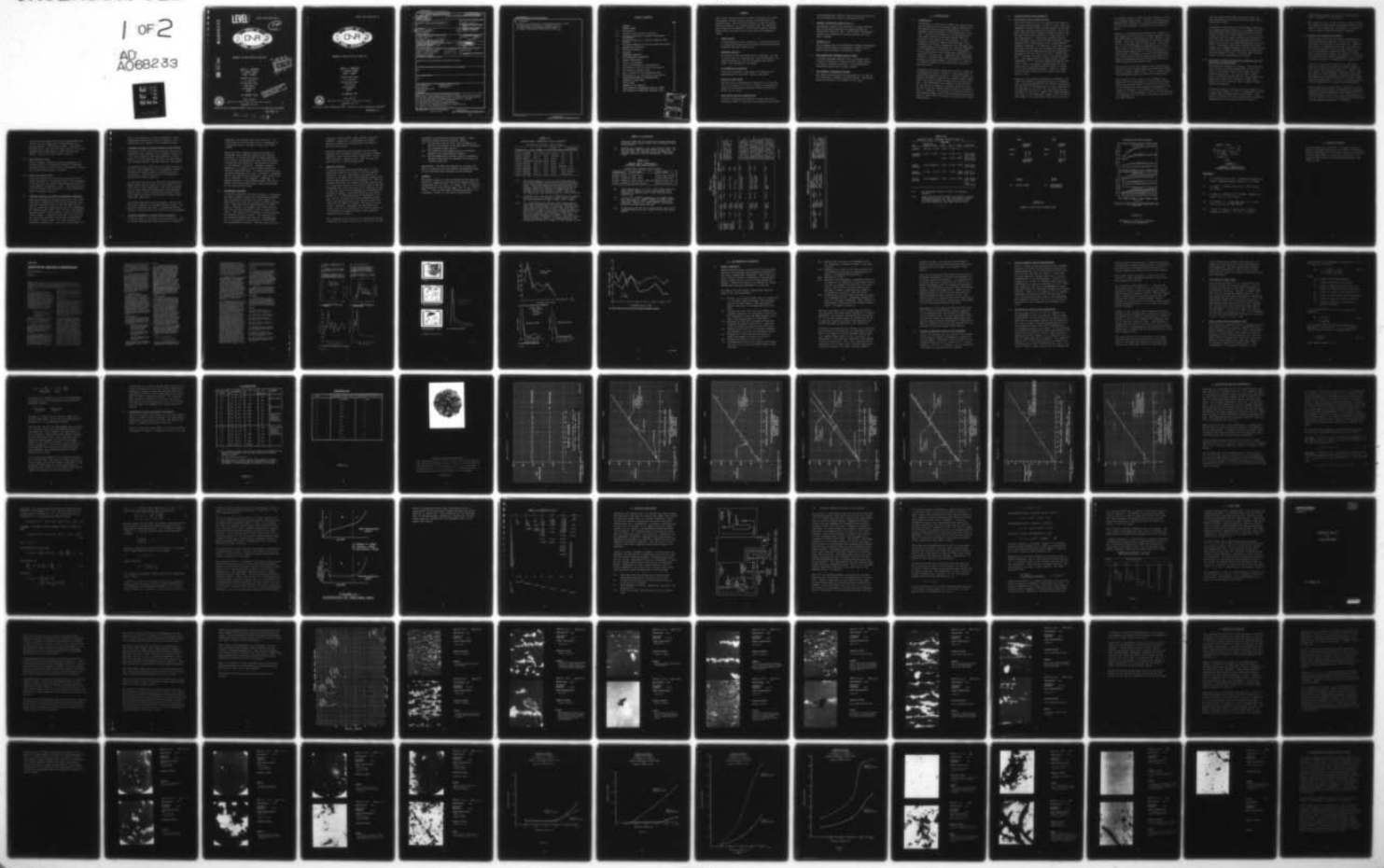

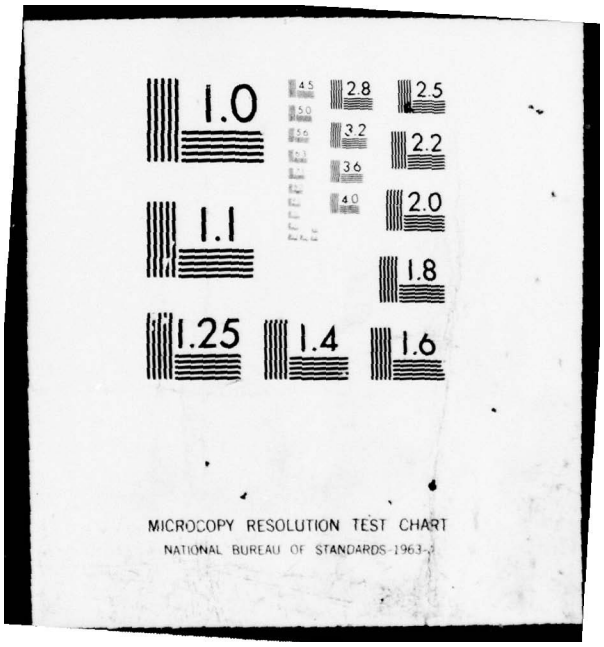
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DANIEL P. ANDERSON
E. RODERIC BOWEN
JOHN P. BOWEN

FOXBORO ANALYTICAL
P.O. BOX 435
78 BLANCHARD ROAD
BURLINGTON
MASSACHUSETTS
01803

16 FEBRUARY 1979

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FINAL REPORT

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PREPARED FOR THE

OFFICE OF NAVAL RESEARCH • 800 N. QUINCY ST. • ARLINGTON • VA • 22217

ENCLOSURE (2)

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Nine areas of investigation are described to improve wear particle analysis for machine condition monitoring through oil analysis. The nine areas are:
1) Use of temper colors to identify wear particles on ferrograms,
2) Quantimet analysis applied to ferrograms,
3) Calibration of the direct reading ferrograph,
4) Particle concentration equilibrium in lubricating oil,
5) Study of an oil sampling filter,

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20. (continued)

6) Support to applications of the delamination theory of wear,
7) Application of ferrography to hydraulic fluids,
8) A more quantitative ferrogram analysis sheet, and
9) Support to The Technical Cooperation Program.

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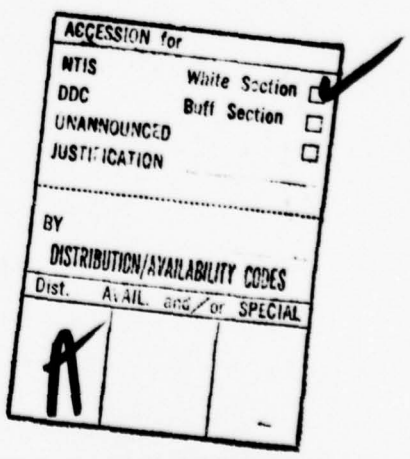


SUMMARY

This report covers work done to further elucidate and refine ferrographic methods of wear particle identification and quantification. Wear particle analysis is used for machine failure prevention, as a machine design aid, for measuring wear induced by contaminants, and for tribological research. Efforts have been made in nine areas which are summarized below:

1. TEMPER COLORS

   A ferrogram may be heat treated on a laboratory hot plate to distinguish between broad classes of ferrous metals by examining resultant temper colors.

2. QUANTIMET ANALYSIS

   An automatic image analyzing system, Quantimet, is used to obtain data for concentration, size distribution, and shape distribution, and can distinguish free metals, oxides, and compounds on ferrograms.

3. DR FERROGRAPH CALIBRATION

   Tests were conducted to determine the linearity and repeatability of the direct reading ferrograph.

4. PARTICLE FILTER STUDY

   Work was done to determine the feasibility of filtering part of an engine's oil flow to obtain a representative sample of the particles generated during the time the filter was in place.

5. EQUILIBRIUM PARTICLE CONCENTRATION

   To better understand the behavior of wear particles, a theoretical model of wear particle generation and capture

was developed which predicts that particle concentration in any machine will reach an equilibrium value.

6. SUPPORT TO NAM SUH'S GROUP AT M.I.T.

Ferrographic analysis was performed to support development of practical applications resulting from the delamination theory of wear. Specifically, ferrographic analysis was performed on aircraft splines with soft metal coatings.

7. HYDRAULIC OIL

Use of magnetizing ions developed for medical ferrography allowed precipitation of non-metallic debris such as might indicate failure in hydraulic systems.

8. MORE QUANTIFIED FERROGRAM ANALYSIS SHEET

A revised ferrogram analysis sheet is proposed which relates the percent of various particle types present, at various ferrogram locations, to the mechanically determined percent area covered reading.

9. THE TECHNICAL COOPERATION PROGRAM

Oil samples were anlayzed by ferrography at six labs in four countries to compare analysis methods. The Foxboro Analytical analysis is included in this report.

1. TEMPER COLORS

1.1 INTRODUCTION

Ferrographic oil analysis is useful for condition monitoring because only a lubricant sample need be provided from the machine under investigation; no other equipment need be provided on the machine under scrutiny. The particles present on the ferrogram carry with them a history of the wear process which has occurred in the engine or other machine. It was, therefore, decided to explore possible means of extracting still further information from ferrograms by a simple method of identifying the chemical components in the machine with the possibility of determining exactly which part of the machine was responsible for creation of the particle. Comparison with ferrograms taken for a machine under normal operation would show whether an excessive number of particles of a particular material indicated an excessive wear rate for a particular part.

Preliminary tests were carreid out in which a number of techniques were used to attempt to find ready means of identifying individual particles. Notably, exposure to gaseous atmospheres, exposure to chemical vapors, immersion into certain chemical reagents and the exposure to heat. The preliminary tests indicated that the first two methods were unlikely to produce effective results but the latter two methods offered promise of practical utility. Moreover, the exposure of certain materials to heat produced temper colors which differentiated between them so clearly that this method was selected for fuller investigation.

1.2 IDENTIFICATON BY HEAT COLORATION

1.2.1 Principles of Color Identification

When iron oxidizes in air, an invisible film grows on the surface which consists of cubic γ Fe_2O_3. When the temperature exceeds 200°C, further growth of the oxide film takes place by diffusion of metallic ions on the metal oxide interface outwards through the oxide film. The main oxide layer consists of α Fe_2O_3 which is a P type semiconductor. Electrons tunnelling from the metal through a thin oxide film are captured by oxygen absorbed on the oxide surface until an equilibrium becomes established. The field set up by these trapped electrons can then pull ions through the oxide film. The growth rate is limited either by the tunnelling of electrons or by the rate of ion drift. Fehlner and Mott[1] consider the latter mode to be the most important. The rate of growth of oxide films is usually logarithmic.[2][3] The most probable explanation for this is that the potential induced across the film gives rise to a potential gradient which is reduced as the film thickness increases. Figure 1-1 illustrates the main features of the growth of an oxide layer on iron.

Because of the electronic mechanism of oxidation, the oxide film formed is remarkably uniform in thickness and in optical properties so that optical interference can give rise to the appearance of colors depending on the thickness of the film. This has been used traditionally in the form of temper colors which appear on tool steel in the temperature range of 200°C to 340°C. They range in this case from a faint straw color for

the thinnest layers at 204°C through a bronze to a blue at the highest temperature. The rate of oxidation and therefore the thickness of an oxide film is determined by the crystallographic orientation of the substrate metal.

Figure 1-2, reproduced from reference (4), shows how the thickness of an oxide film on metal depends on time and temperature of heating and on the condition of the surface. Note that the thickness of the film is asymptotic to a limiting value as time passes. The thickness of this film depends on temperature and, in the case cited, on the crystallographic orientation of the surface under investiation. It would be possible in this instance to develop a procedure for identifying the various crystal faces by heating the material at a range of temperatures and selecting those which produced films which gave temper colors.

The results of this investigation show that different metals and alloys require heating at different temperatures to produce temper colors. Thus, a similar system of discrimination may be devised for unknown metals.

The presence of water vapor in the atmosphere may affect the rate of oxidation by altering the surface potential and affecting the structure of the film.[5] It is believed that the procedures recommended in this report are unlikely to be affected by the range of variation in relative humidity likely to be encountered in a workroom, but the effect of extreme conditions has not been examined.

The only stable oxide formed by nickel is NiO (a P type semiconductor) and this metal also gives rise to interference colors.

Preliminary investigation of color changes resulting from temperature was carried out on a number of metals and those which showed significant response are described in Table 1-I. Metal plaques 2" x 1/2" x 1/16" thick were cut from sheet stock with the exception of the AISI 52100 steel which was machined from a ball bearing and the cast iron which was machined from round stock. Preliminary tests were conducted by setting plaques on a standard laboratory hotplate and observing surface color changes as temperatures were allowed to rise from ambient to 510°C. The total time for temperature rise was approximately 15 minutes.

1.2.2 The Effects of Heating Austenitic Stainless Steel and Martensitic Stainless Steel

Each sample was heated for 3 minutes, and it was seen in the series of steps betwwen 482°C to 704°C that there is progression from no color effect at all to the deep blue effect. The case of 538°C (1000°F) shows a difference between the two steels because the austenitic steel has not started to change color, whereas the other steel has begun to show a distinct light straw pattern.

A separate series of screening tests were made with a set of these plaques in a kiln to temperatures of 704°C (1300°F) using a fixed time for each sample. Progressive blue oxide color was observed with increase in temperature but no distinction could be made to

differentiate between the austenitic and martensitic types. See Table 1-II for details.

The results of tests on the thin metal plaques offered the promise of discrimination between materials on the basis of color change and, accordingly, an investigation was made on heating ferrograms themselves.

1.2.3 Method of Investigating Ferrograms

Three methods of heating ferrograms were employed, a standard laboratory hotplate, a kiln, and a special tube which was used with an induction coil. Each of these pieces of equipment were shown to be effective on the metal selected within certain limitations as far as availability, temperature range, efficiency, rate of heating and accuracy is concerned. In view of its simplicity and relative availability, the standard laboratory hotplate is recommended for general use.

A series of tests were carried out on particulate material prepared by rubbing test samples against a test rig as illustrated in Figure 1-3. Sixteen (16) oil samples, each containing a different type of metal wear particle, were prepared. These wear particles were generated in approximately 100 ml of MIL-L-23699 synthetic polyester oil. To date, one hunderd nineteen (119) ferrograms have been made from these samples.

Initial heating experiments were conducted in a kiln-type furnace using certain time/temperature parameters. Subsequent heating experiments were conducted with an induction heater tube (I.H.T.) test rig developed for use as a rapid and more accurate medium for heating and applying gaseous atmospheres to ferrograms.

Initial results showed that certain key metallic particles are very susceptible to identification by heating methods. This group includes: AISI 52100 bearing steels, AISI 1018 low carbon steels, cast iron, phosphor and leaded bronzes, nickel and stainless steels. Table 1-III gives typical results.

1.2.4 Heat Resistant Group

Silver, cadmium, chromium, aluminum, magnesium, titanium and zinc do not generally exhibit a sufficient reaction to heat as far as color is concerned to enable any reliable distinctions to be made.

1.2.5 Effect of Particle Size

Consistent behavior was observed on the part of the larger particles at the entrance area of the Ferrograms. Very small particles usually found below 50 mm did not always develop interference colors. This may be due to an insufficiently wide film area to reflect sufficient light to register optically.

1.3 FERROGRAM EXPOSURE TO GASEOUS ATMOSPHERES (ANHYDROUS)

Selected ferrograms with metal particles of AISI 52100 alone and in combination with the more chemical sensitive metal particles such as lead and brass were exposed to oxidizing, reducing and corrosive atmospheres. The anhydrous gases used, other than air, were ammonia, hydrogen sulfide, carbon monoxide, carbon dioxide and sulfur dioxide. A special double wall tube utilizing an Inconel base for induction heating of ferrograms was used to conduct tests. The time, pressure, and temperature parameters of these tests are in Table 1-IV.

None of the particles on these ferrograms in these experiments exhibited any special change in color or morphology due to exposure to the anhydrous gases.

1.4 FERROGRAM EXPOSURE TO VARIOUS CHEMICAL VAPOR SYSTEMS

Ferrograms of AISI 52100 metal particles alone and in combination with aluminum, zinc, phosphor, bronze and silver were exposed to moisture-saturated air plus vapors of certain chemical solutions of sodium hydroxide, hydrogen sulfide, hydrogen chloride, and ammonia.

A ferrogram of AISI 52100 particles raised to the normal blue oxide temperature in an atmosphere of water-saturated air showed evidence of passing the blue oxide phase. Indications are that the presence of moisture accelerates oxidation.

All the metal particles were relatively unaffected by ammonia vapor and the vapor from the solution of the fixed alkali, sodium hydroxide. AISI 52100, aluminum and zinc were apparently unaffected by the hydrogen sulfide vapors, while silver and the phosphor bronze both showed some uneven discoloration by these vapors under test conditions.

AISI 52100, aluminum and zinc ferrograms were grossly affected by exposure to hydrogen chloride vapors. All particle morphology was lost, so differences between aluminum, zinc and AISI 52100 could not be distinguished.

1.5 FERROGRAM IMMERSION IN DILUTE ACIDS AND ALKALIS

A limited series of experiments were conducted in order to rapidly distinguish between particles of aluminum,

magnesium, and titanium metal wear particles. All three types of particles may occur in combination an a ferrogram and are resistant to heat up to 482°C (900°F).

Relatively short immersion times (30 seconds) of ferrograms with aluminum, magnesium and titanium particles, in dilute solutions of sodium hydroxide (0.1 normal), and hydrochloric acid, produce results predicted by the behavior of these metals according to the technical literature. Aluminum, which is amphoteric, is soluble in both dilute hydrochloric acid and sodium hydroxide. As visible reaction occurs, the metal disappears and a salt is produced. Magnesium reacts only with dilute hydrochloric acid, while titanium is resistant to both reagents. Therefore, it appears practical to distinguish between these three metals, which look similar when viewed on ferrograms, by the above mentioned test.

1.6 RECOMMENDED PROCEDURE

It has been shown that the heat treatment of ferrograms provides a powerful method for discriminating between the four materials selected for study, namely, the AISI 52100 steel, cast iron, nickel, and 304 stainless steel. These metals are representative of a wider range of material; for example, AISI 52100 steel has very much the same response to heat as carbon tool steels. The reaction of ferrograms to heating reveals four distinct groups of metals. The procedure for discriminating between particles on a ferrogram are for it to be heated for 90 seconds at 330°C (625°F) and photographed on cooling. Then the process may be

repeated at 400°C (750°F), 480°C (900°F), and 540°C (1000°F). Comparison of photographs will enable particles present to be characterized according to the four alloy groups.

Materials remaining uncolored after the final heat treatment may be examined chemically and any aluminum, magnesium, and titanium could be identified. A residue of material, chromium, zinc, lead, tin and cadmium would still remain unidentified.

1.7 SEM/X-RAY ANALYSIS

A scanning electron microscope (SEM) with an x-ray energy spectrometer may be used to further identify particles. An x-ray spectrometer was recently installed on the SEM at The Foxboro Company research labs and has been available to the ferrograph lab. This instrument identifies the elements that emit characteristic x-rays once excited by the electron beam of the SEM. Ferrograms must first be coated with a conductive layer so that the electron beam scanning the ferrogram may be returned to ground. A gold/palladium coating, which worked well for SEM examination of ferrograms in the past, was not suitable for particle analysis because some of the gold/palladium x-ray emission peaks coincided with the peaks of elements that were to be identified. Therefore, ferrograms are now coated with carbon, which is of sufficiently low atomic number not to interfere with wear metal peaks, when elemental identification is sought.

This technique has been useful for identifying the main constituent of target particles but has so far not been

successful at identifying alloying elements. Three obstacles prevent detailed analysis, namely:

(1) The particles are not flat, which assumption is made by the software of the minicomputer analyzing the offcoming energy spectra.

(2) The software itself appears prone to producing anomalous and irreproducible results.

(3) The ferrogram glass contains various interfering elements which cannot be assumed to be present in constant proportion.

Nevertheless, the SEM/x-ray analyzer is a useful tool and it is expected that with effort and experience some of the above-mentioned problems will be mitigated.

1.8 APPENDIX

The salient results of this investigation have been published in a paper entitled "The Use of Temper Colors in Ferrography" by E.R. Bowen, J.P. Bowen, and V.C. Westcott which appeared in the journal Wear, Vol. 44, pp. 163-171 (1977). A copy of this paper is appended because it is convenient to refer to the colored illustrations.

TABLE 1-I

HEATING TESTS, SCREENING OF METAL PLAQUES(1)

Surface Color Changes, Metal Plaques

Temperature	AISI 1090	AISI 52100	Cast Iron(3)	Nickel	Stainless Steels(2)
204°C (400°F)	Blue	Part Blue	Bronze	N/C	N/C
232°C (450°F)	Blue	Blue	Bronze	N/C	N/C
260°C (500°F)	Blue	Blue	Blue	N/C	N/C
287°C (550°F)	Blu-Grey	Blu-Grey	Blue	N/C	N/C
315°C (600°F)	Grey	Grey	Grey	N/C	N/C
398°C (750°F)	Grey	Grey	Grey	Bronze	N/C
420°C (800°F)	Grey	Grey	Grey	Blue	Bronze
471°C (880°F)	Grey	Grey	Grey	Blue	Blue(4)
510°C (950°F)	Grey	Grey	Grey	Blue	Blue

(1) All metal plaques 2" x 1/2" x 1/16" thick were cut from existing sheet stock except AISI 52100 machined from a ball bearing and cast iron machined from round stock. Tests were conducted by placing plaques on a standard laboratory hotplate (Corning PC-35) and observing surface color changes as temperature was allowed to rise from ambient to 510°C. Total time for temperature rise was approximately fifteen minutes.

(2) Stainless steel results are a composite of the results of the tests on two austenitic types (304SS, 321SS) and three martensitic types (410SS, 416SS, 430SS).

(3) It is significant that the cast iron plaque used in this metal screening test was made by machining with tool steel, and although it was slower to develop blue oxide surface color than the AISI 1090, AISI 52100 steels did so readily at a slightly higher temperature. This is in contrast to behavior of ferrograms of cast iron wear particles under heating in later tests, which resisted oxidation up to 350°C. The effect of surface contact of normally oxidation-resistant metals, with low oxidation metals, was demonstrated by burnishing the surface of a plaque of 430SS against a wire

TABLE 1-I (continued)

wheel and under the very same heat testing conditions as above, a blue oxide surface color developed around 371°C (700°F).

(4) Surface color changes of all the stainless steels was less distinct than the other metals in the test. For the most part, the surfaces of the stainless steel plaques exhibited a mottled appearance. (See Table 1-II.)

TABLE 1-II

HEATING TESTS, SCREENING OF STAINLESS STEEL METAL PLAQUES(1)

Surface Color Changes, Metal Plaques

Temperature	AISI 304SS	AISI 430SS
482°C (900°F)	Light Straw	Very Light Bronze
537°C (1000°F)	Light Straw	Darker Bronze(2)
593°C (1100°F)	Light Bronze, Some Blue	Dark Bronze, Blue
704°C (1300°F)	Mottled Blue(3)	Mottled Blue(3)

(1) Metal plaques were 2" x 1/2" x 1/16" thick pieces of sheet stock, heated in a kiln type furnace, for a duration of 3 minutes each at the above specified temperatures.

(2) At the 537°C (1000°F) temperature, the 304SS plaque was light straw vs. darker bronze for 430SS, indicating, initially at least, a greater resistance to oxidation. However, at 593°C (1200°F), the surface color of each was about the same.

(3) It was noted that the blue oxide surface color of the stainless steels was not a solid hue like the carbon steels.

TABLE 1-III

TYPICAL HEATING TESTS
FERROGRAMS WITH METALLIC WEAR PARTICLES THAT DISPLAY TEMPER COLORS

Metals	Equip.	Temp.	Time	Surface Condition	Ferrogram No.	Comments
Phosphor Bronze (52100)	I.H.T.	287°C (550°F)	3 min.	Distinct Blue	F1007	Phosphor and leaded bronze sensitive to oxidation at temperatures lower than other metals listed.
Leaded Bronze (W/52100)	I.H.T.	300°C (575°F)	3 min.	Distinct Blue	F996	
	I.H.T.	371°C (700°F)	90 sec.	Blue Color	F996	
AISI 52100	I.H.T.	328°C (625°F)	90 sec.	Distinct Blue at Entry Deposit	F1149	Color most distinct in larger particles (E.D.)-smaller particles below 50 mm have passed oxide phase.
Cast Iron (52100)	I.H.T.	320°C (610°F)	90 sec.	Cast Iron Bronze (52100 Blue)	F1150	Cast iron colors at 328°C through 371°C range from dark bronze to blue depending on particle size, crystallographic orientation, possible composition variations, etc.
		371°C (700°F)	90 sec.	Cast Iron Blue (52100 Faded)	F1150	
Nickel (52100)	I.H.T.	482°C (900°F)	90 sec.	Nickel Distinct Blue	F955	Nickel particles turn blue in this temperature in most, but not all tests. Humidity may be in question.

(continued...)

TABLE 1-III (continued)

Metals	Equip.	Temp.	Time	Surface Condition	Ferrogram No.	Comments
AISI 304SS	Kiln	537°C (1000°F)	5 min.	304SS, Bright but uneven Blue	F920	650°C upper limit of heat resistance of ferrogram slides. Re: Table 1-II, SS plaque stilled mottled blue effect up to 704°C.
	Kiln	698°C (1200°F)	3 min.	304SS, Bright but uneven Blue	F910	

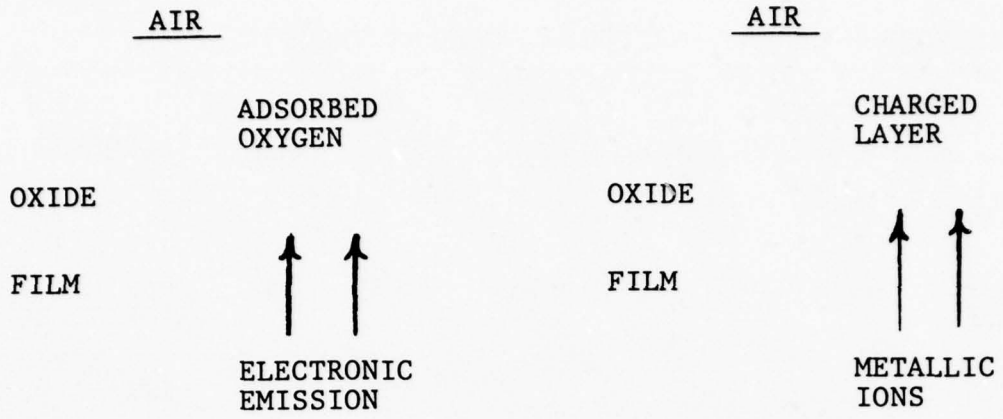
TABLE 1-IV

ANHYDROUS GASES, FERROGRAM EXPOSURE TESTS (1)

Gas	Explosive Limits in Air	Exposure Time	P.S.I.	Temp.	Ferrogram
Ammonia	(16.2% - 25.0%)	3 min.	10 PSI	R.T.	-----
Hydrogen Sulfide	(4.3% - 4.6%)	3 min.	10 PSI	R.T.	F93J Lead/ AISI 52100
		3 min	10 PSI	100°C	F940 Brass/ AISI 52100
Carbon Dioxide	(non-flammable)	3 min.	10 PSI	300°C	F936 Lead/ AISI 52100
Carbon Monoxide	(12.5% - 74.2%)	3 min.	10 PSI	315°C- 320°C	F932 (2) AISI 52100
Sulfur Dioxide	(non-flammable)	3 min.	10 PSI	300°C	F941 Brass/ AISI 52100
					F932 AISI 52100

(1) All ferrograms showed no effect from gaseous exposure.

(2) Carbon monoxide (CO) normally considered a reducing atmostphere, but F932 at 320°C and under a blanket of carbon monoxide, the larger AISI 52100 wear particles showed the blue oxide surface color.



(a) INITIAL STAGE

(b) MECHANISM OF FILM GROWTH

FIGURE 1-1

GROWTH OF OXIDE FILM ON HEATED IRON

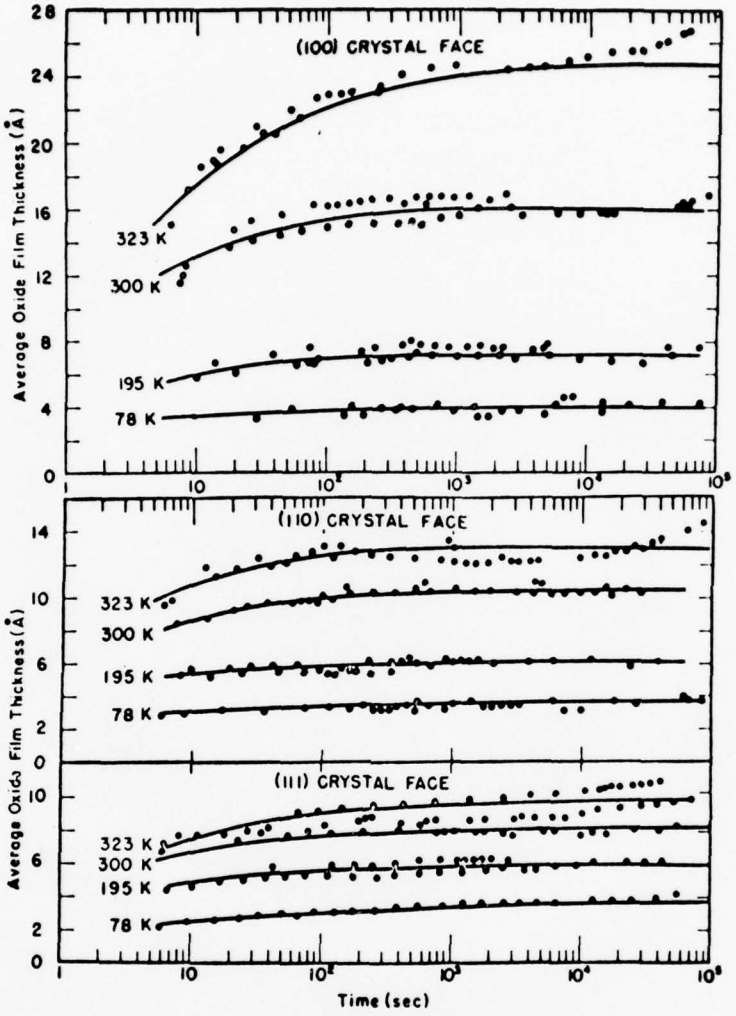


Fig. 7. Oxidation of various single-crystal copper surfaces as a function of temperature. The circles and dots represent different samples. (After Rhodin, Ref 39)

FIGURE 1-2

DEPENDANCE OF OXIDE FILM THICKNESS
ON TIME AND TEMPERATURE

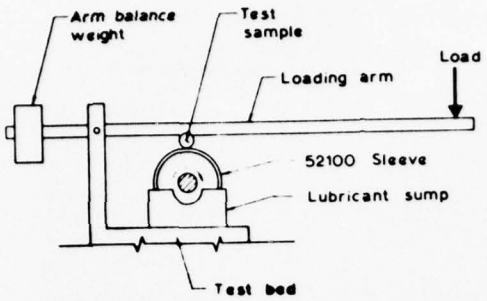


FIGURE 1-3

SCHEMATIC OF TEST RIG TO
GENERATE METAL WEAR PARTICLES

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2. QUANTIMET ANALYSIS

Work performed under subcontract to Swansea University towards automating some quantitative aspects of ferrogram analysis is presented in their paper "Quantitative Analysis in Ferrography" which is reprinted by permission of the Council of The Institution of Mechanical Engineers from Tribology 1978.

C44/78

QUANTITATIVE ANALYSIS IN FERROGRAPHY

B.J. ROYLANCE, M.H. JONES,
Department of Mechanical Engineering, University College of Swansea
and
A.L. PRICE,
Swansea Tribology Centre

SUMMARY Examples are given indicating the application and scope of quantitative analysis in Ferrography; they include optical density, direct reading ferrograph, and analysis by Quantimet. The Quantimet system, when used in conjunction with computerised data processing, provides rapid automatic analysis of the ferrograms. Wear data are generated in terms of particle composition, size and shape distribution, with particular reference to the identification of free metals, oxides and compounds occurringas a result of wear in plant machinery components.

INTRODUCTION

1. Since the introduction of wear particle analysis by Ferrography in 1972,[1] it has rapidly found application in the field of machinery health monitoring.[2] Wear particles or other debris, collected in lubricating systems, are analysed by both optical and electron microscopes to establish qualitative information on shape,composition and size distribution.[3] Quantitative information is obtained by optical density measurements of the particles deposited on the slide,[1] or from the Direct Reading Ferrograph.[4] Measurement of the optical density provides an indication of the size distribution of particles. The change in size with position along the slide is utilised to establish the Severity Index, I_S where

$$I_S = (A_L + A_S)(A_L - A_S) = A_L^2 - A_S^2$$

A_L = maximum percentage area in the entry deposit (≈ 55 mm)

A_S = maximum percentage area at the 50 mm position.

Thus the product of total particle rate and the difference in the production of the large particles (> 5 μm) to the small particles (1 - 2 μm) is used to represent a measure of the wear condition in plant machinery.

In the Direct Reading Ferrograph, the optical densities of wear debris deposited on the walls of a glass precipitation tube are measured at two specific locations 5 mm apart, thereby enabling the determination of the Severity Index defined above except that the A_L and A_S terms are denoted as D_L and D_S, respectively.

2. An alternative method for quantifying information from a ferrogram utilises the image analysing system, Quantimet.[5] Wear debris extracted during tests undertaken with a twin disc machine were analysed to obtain data in terms of the number, size and distribution of wear particles. A correlation between running-in wear and performance characteristics was achieved which has prompted further work in the utilisation of Quantimet. The main purpose of this paper is to describe the techniques which have been developed recently to enable rapid, automatic analysis of ferrograms with the aim of providing detailed information on the wear behaviour in machinery systems.

QUANTITATIVE ANALYSIS BY CONVENTIONAL METHODS

Optical Density

3. The relationship between the ferrogram entry deposit and the iron content of used lubricating oils has been established from optical density readings and compared with other methods of measurement such as spectrographic oil analysis, (SOA) and X-ray fluorescence, (XRF).[6,7] Samples taken from a jet engine[6], showed that they contained a large amount of oxide or chloride particles to which the ferrograph is insensitive, and a number of particles so large that the emission spectrometer was unable to detect them. Later work[7], showed that provided the wear regime does not change, the entry volume can be related to SOA readings.

4. An important consideration in the application of ferrography is the opportunity it provides for examination in the optical microscope to obtain qualitative information concerning the nature and morphology of the wear debris which can then be related to quantitative information. It is important therefore to establish how ferrography, which is based on oil sampling, compares with more direct measurements of the wearing surfaces. To establish a basis for comparing optical density measurements with other methods, a test programme was undertaken in the authors' laboratory in which a series of wear measurements were made using the four ball apparatus. The Institute of Petroleum's standard scuffing test procedure, (IP 239) was adopted, in which the average wear scar diameter of the balls at each load was measured after running for 60 seconds at 1500 rev./min when testing with HVI 60 lubricant. The weight loss experienced by the balls was also monitored, and both sets of measurements were compared with optical density measurements made on samples of oil taken after each test, Fig. 1, in which there is general agreement evident between all three methods of

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measurement. The wear scar diameter and weight loss measurement relate directly to the wear of the solid material, whereas the ferrograph analysis is dependent on the wear debris collected in the oil sample. The implementation of correct sampling techniques for monitoring industrial applications is clearly of paramount importance.[8]

5. The heating of ferrograms to distinguish materials by colour improves the facility for monitoring wear in practical applications.[9] Utilisation of this technique to monitor the running-in wear behaviour of diesel engines has been reported,[10,11] in which the Severity Index, I_S is correlated with spectrometric data. The percentage area covered by each material is plotted versus distance along the ferrogram. Use of heated ferrogram analysis techniques enables slight changes in material composition with change in wear behaviour to be monitored. There is good correlation generally with spectroscopy measurements, but I_S values exhibit a greater sensitivity. This was particularly evident during the initial period of running.[11]

Direct Reading Ferrograph (DR)

6. Preparation of a ferrogram and the subsequent analysis requires considerable time (> 30 mins. per sample). The DR facility however enables results to be obtained quickly, (< 10 minutes per sample). The results of a four-ball scuffing test are shown in Fig. 2, in which the DR values are compared with the wear scar diameter as a function of load. Scott & Westcott have demonstrated how the DR method was used to monitor the life test of a large gear-box.[12] When a baseline for the operation of a machine had been established, routine sampling and analysis by DR proved to be efficient and reliable. In new applications, a change in I_S value signals the need for more comprehensive analysis to establish information on the morphology of the particles in the lubricant.

Analysis by Quantimet

7. To establish a range of techniques for quantitative analysis by Quantimet, a number of ferrograms have been examined which were taken from various conditions of operation. The investigation is being undertaken in three stages as follows:-

1. Establishing the means for rapid processing of routine information, such as optical density measurements, by automatic methods covering the whole slide.

2. Quantitative measurement of wear particles distinguished by their material designation e.g. free metal, oxides, etc.

3. Quantitative measurement of wear particles distinguished by their wear mechanism.

The results reported in this communication describe the methods devised in 1 and 2 above. The third stage is the subject of further investigation.

Procedure

8. Preparation of ferrograms is carried out in the normal manner and then placed on the stage of a Reichert Type 1 optical microscope for examination. The microscope stage is fitted with facility for automatic traversing which permits a full two-dimensional analysis of the ferrogram. Reflection and Transmission light sources are available in normal and polarised condition. A quantimet 720 image analysing system is linked directly to the microscope by means of a purpose built 720 line Plumbicon Scanner. Variations in light density and contrast level provide a powerful tool for distinguishing particle groups, such as strings of free metal particles deposited on the ferrogram, which can then be analysed in terms of dimensional parameters such as area, perimeter, chord width, etc. The results of analysis by Quantimet are displayed in visual digital format, and are also available in punch tape form. The punch tape is used as input data for a series of computer programmes developed during this investigation to calculate the wear parameters and also display the results graphically. Means are thus provided for processing data by fully automatic methods which can analyse rapidly the whole of the slide.

Results of Application

9. The four ball oil samples, analysed previously by the Direct Read method, were analysed by Quantimet and plotted as peak percent area covered when viewed in transmitted light, Fig. 2. In the wear transition region, there is close agreement with the wear scar diameter measurements in terms of the wear rate. The possibilities for establishing other useful wear indicators have been investigated with particular reference to defining shape factors derived from the individual dimensional parameters measured by Quantimet. One such factor, effectively an aspect ratio, defined in terms of average length to breadth ratio of the particles displayed in the field of view, shows promise of becoming a useful parameter and which complements the existing optical density measurement used in ferrography. The particle groups in a field of view are monitored to establish data in terms of a size count and intercept. The size count represents the number of particle groups within a specified size range, as defined by their chord width. The size ranges are pre-selected, and for this investigation were as follows:- > 1, > 2, > 4, > 8, > 16, > 32 pp (1 pp = 1 μm) i.e. number of particles > 1 pp, etc. The intercept parameter measures the vertical dimension as displayed on the screen and sums the values for all the individual particles, (or groups of particles detected as a single particle) thus giving a single total value in picture points (pp). On this basis the shape factor is defined as

$$S.F = \frac{\Sigma I}{\Sigma C}$$

where ΣI = Total Intercept value

$$\Sigma C = (>1-2).1.5+(>2->4).3+(>4->8).6 +(>8->16).12+(>16->32).24$$

An example of its application is shown in Fig. 3 representing an analysis undertaken for a jet engine oil sample. The variation in area with

ferrogram distance is nominally constant. Visual inspection of the field in the optical microscope at different positions along the ferrogram revealed that long strings of particles in the entry region changed to a 'globular' shape further down the slide. When plotted as a function of shape factor, the aspect ratio varies from 4.25 in the entry region (strings) to 1.0 (globular) at the 50 mm position on the ferrogram. The application of this technique is being further evaluated in relation to stage 3 of this investigation.

10. To distinguish particles in terms of their material designation, two basic approaches are used either separately or in combination, as circumstances dictate. The first approach utilises the extensive range of contrast settings available in Quantimet for detecting different levels of light and background in conjunction with the means available at the microscope for viewing with different light sources. Figures 4 and 5 demonstrate how this technique is utilised in distinguishing between free-metal and red oxide when viewing the field in transmitted, polarised light. By using combinations of reflected, transmitted, and polarised light in association with selected colour filters, oxides and polymeric material can, for instance, be readily identified in relation to free-metal particles, and their respective levels and distributions are then quantified by the techniques described previously.

11. The second approach is to heat the ferrograms to distinguish free-metals by their temper colour. Particle analysis was carried out on oil taken during the monitoring of a Perkins Research V8.540 diesel engine of 8.83 litres swept volume with a nominal rating of 134 kW (180 hp). This engine had been used for a piston research programme where some failure was considered likely. Engine running conditions were similar to those recorded previously and reported elsewhere.[11] The main wear constituents of interest in this investigation were steel and cast iron. The problem the analysis posed was to determine how steel and cast iron were wearing with time during the running-in period of this engine. Analysis of unheated ferrograms was undertaken first to determine optical density measurements in the Ferrograph Reader, and these are compared with results of analysis by Quantimet for the first few hours of running time, (Fig. 6). Optical examination, coupled with micro-probe analysis, indicated the presence of steel and cast iron wear particles, and by heating the ferrograms to 330°C for 90 seconds, they were easily distinguished by colour; steel turning blue, cast iron a bright straw colour. Analysis by Quantimet was then undertaken by detecting for steel, (darker than the background) and cast iron, (lighter than the background) when viewed in normal reflected light. The results of Figure 7 reveal the distribution of steel and cast iron particles with distance along the ferrogram for two running times. A clearer picture of the behaviour emerges when the peak percent area for both materials respectively is plotted with running time, (Figure 8). The results indicate that the cast iron is initially running-in at a higher rate compared with steel. After the first two hours the wear rate of the cast iron is noticeably lower than that for the steel, which continues to wear at a nominally constant rate.

Conclusions

12. Correlation of quantitative measurements used in Ferrograph analysis with other methods of wear measurement is generally acceptable, and in certain instances has shown promise of being a more sensitive indicator of changes in the wear process. The Direct Read facility is used primarily for routine condition monitoring, where it has proved to be relatively cheap, rapid and reliable. The application of the Ferrograph Analyser in conjunction with Quantimet, provides important additional data when unexpected or critical operating and wear conditions arise in practice which demand a detailed evaluation of the wear situation.

Methods have been established to enable rapid, automatic analysis of ferrograms and to distinguish wear particles by their material designation. Further work is now being undertaken to establish the feasibility of using Quantimet to quantify wear data in terms of their wear mechanism.

Acknowledgements

The assistance of Messrs. P. Beynon, Y. Eren and E. Uslu in the wear testing and processing of some of the data reported in this paper is greatly appreciated. The authors are also indebted to Foxboro/Trans-Sonics Inc. for permission to publish part of the work (Figures 3 - 5) undertaken under Contract No. N00014-74-C-0135.

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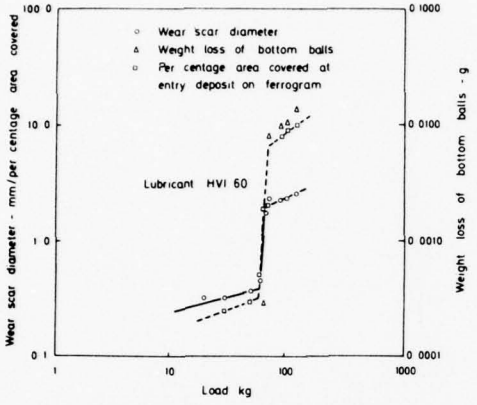

Fig. 1 Four ball scuffing test – comparison of wear measurements

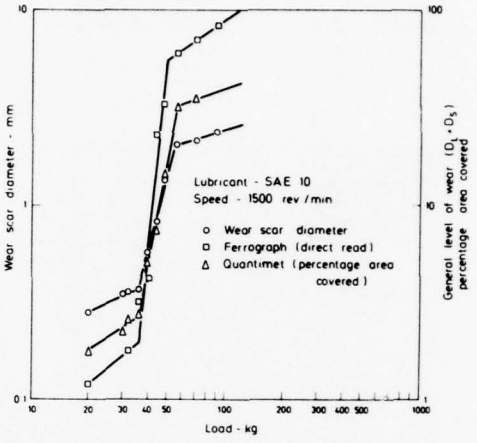

Fig. 2 Four ball test – correlation of Ferrograph results with wear scar diameter

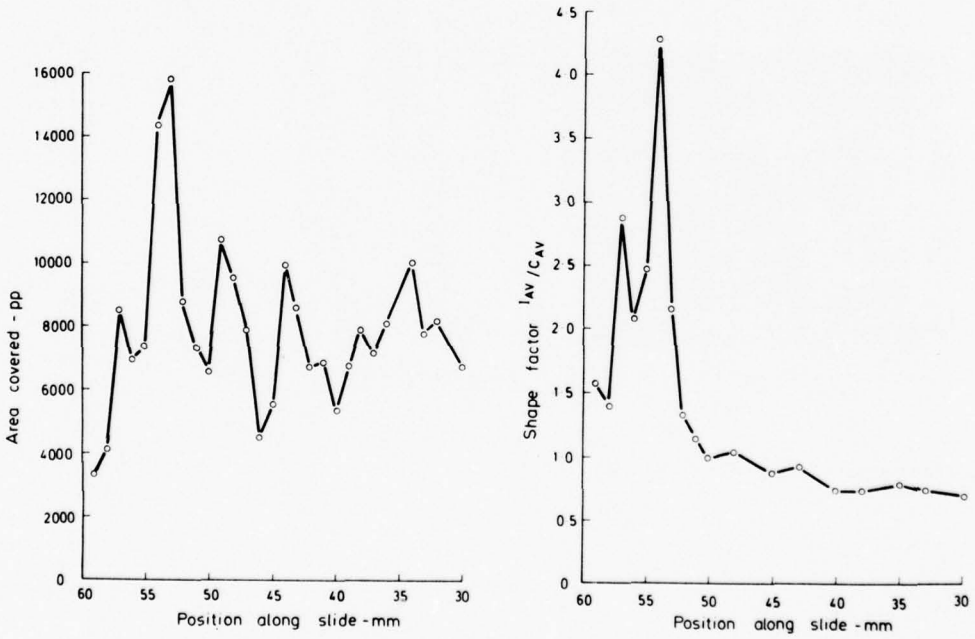

Fig. 3 Quantimet analysis of free-metal particles – use of shape factor

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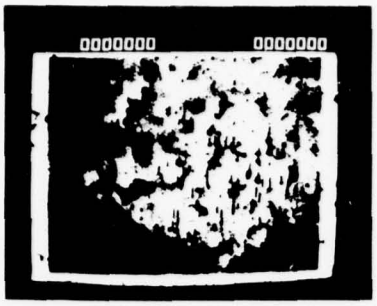
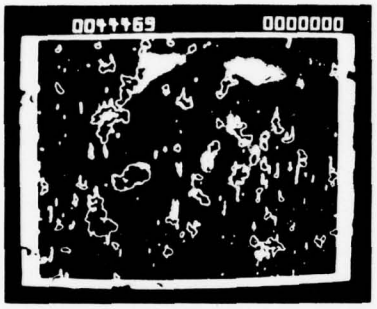
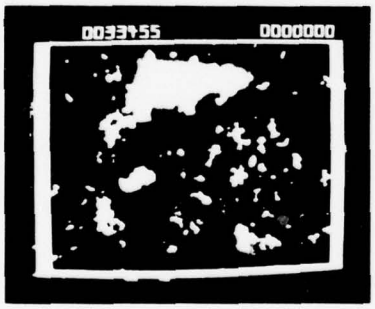


a Normal field



b Detecting for particles darker than background in transmission — area count of field



c Detecting for red oxide particles in polarized light — area count of field.

Fig. 4 Utilization of polarized light to detect red oxide

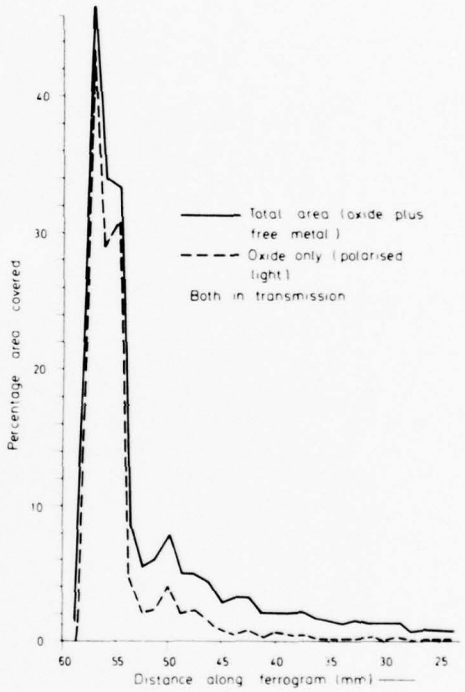


Fig. 5 Proportion of oxide in total deposit

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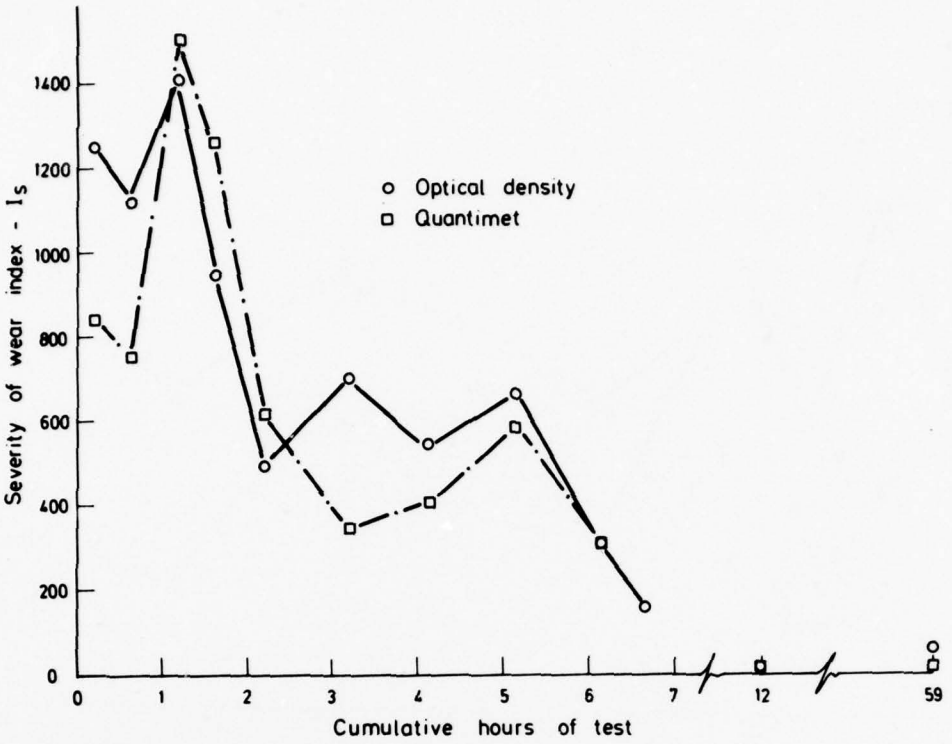

Fig. 6 Running-in wear as a function of test time – diesel engine test

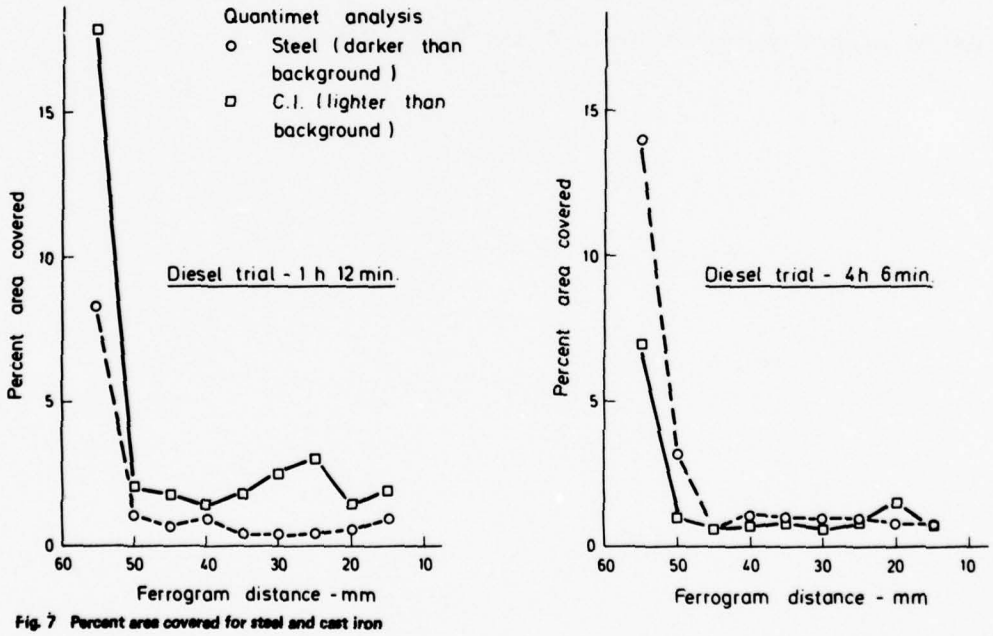

Fig. 7 Percent area covered for steel and cast iron

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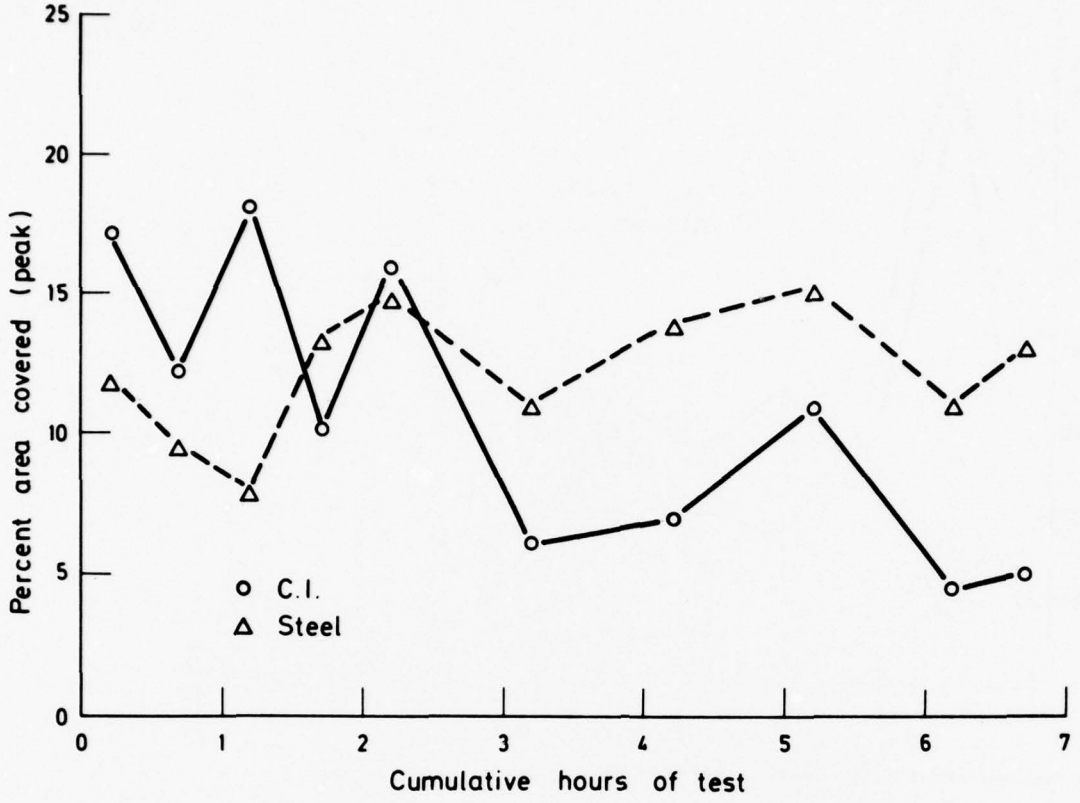

Fig. 8 Wear of steel and cast iron during running-in (diesel engine test analysis by Quantimet)

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3. DR FERROGRAPH CALIBRATION

3.1 SAMPLE PREPARATION

Samples of known weight concentration of ferrous wear particles were prepared and subsequently analyzed by the direct reading (DR) ferrograph. These tests were run in order to obtain a calibration of the DR ferrograph in which the iron in the oil was weighed by a balance. Calibration curves are presented for normal rubbing wear particles generated in a gear box.

The samples of known weight concentration were prepared in the following manner:

(1) Passing 1 cc of used transfer case oil mixed with 1 cc of fixer solution through a DR ferrograph tube in the usual manner, thus causing ferromagnetic particles to be deposited within the tube.
(2) Flushing the tube, while the tube remains continuously subjected to the magnetic field of the DR ferrograph to retain the ferromagnetic particles, thus rinsing away the other debris.
(3) Removing the tube from the magnetic field and flushing with fixer solution into a clean container to remove the particles from the tube.
(4) Passing the contents of the container through a pre-weighed 0.4 μm pore size Nucleopore filter.
(5) Flushing the filter with fixer solution to remove any remnant oil from the particles
(6) Allowing the filter to dry in air.
(7) Postweighing the filter on a Mettler H15 balance accurate to $\pm$0.1 mg to determine weight of the particles.

(8) Adding fixer solution to a preweighed bottle and reweighing to determine weight of the fixer solution.

(9) Submerging the filter in the fixer solution and ultrasonically agitating for approximately 15 minutes to redisperse the particles.

(10) Removing the filter.

(11) Adding oil and reweighing to determine weight of oil added to the dispersion of particles in fixer solution to increase the viscosity of the solution so that particle settling velocity will decrease, allowing a representative sample to be withdrawn, by pipette, from the bottle.

(12) Preparing dilutions by adding the above solution to a preweighed bottle, reweighing, adding filtered oil, and again reweighing. Thus, samples of known weight concentration were obtained without resort to volumetric dilution.

The first step above, that of isolating the metallic wear particles from other debris through use of the DR ferrograph, was essential considering that filtration of 1 cc of used transfer case oil yielded about 20 mg of material, whereas filtration after separation by the DR ferrograph yielded about 1 mg of material.

Contention that wear particle analysis or that particle size distribution analysis may be undertaken directly from an oil sample, as certain European workers maintain, appears questionable at best, in view of the obscuration to wear particles inevitable when viewing a gross oil extraction. The filter, mentioned above, upon which 20 mg of debris was collected, when microscopically examined, was almost entirely opaque to

transmitted light, and revealed only occasional metallic particles with reflected light where those particles were, by chance, not covered by other debris.

After the wear particles have been isolated from all non-magnetic material, filtration was necessary to accurately weigh the particles. It is expected that a certain fraction of particles less than 0.4 μm in effective diameter were lost through the Nucleopore filter, thus shifting the particle size distribution somewhat toward the larger sizes. Figure 3-1 is a photomicrograph of the filter with wear particles after allowing the fixer solution to dry. Non-central regions of the photo are out of focus due to the curling of the filter. Notice that there appears to be little else but metallic particles.

Redispersion of the particles from the filter back into solution, accomplished by vigorous agitation in an ultrasonic bath, was assured by examination of the cleaned filter; the outer edges where filtration had not taken place showed approximately the same occasional particle distribution, indicative of particle capture as the filter was removed from the solution, as did the central filter portion.

3.2 SCATTER OF READINGS CAUSED BY THE INSTRUMENT

Figure 3-2 presents data for repetitive DR readings of the same oil sample to demonstrate scatter for the instrument. Horizontal lines are drawn for the average values for the "L" (large) and "S" (small) readings. For the "L" readings, the one anomalously low reading is excluded from the average.

3.3 PLOTS OF READINGS VERSUS CONCENTRATIONS

Table 3-I presents data resulting from DR ferrograph readings of two sets of known weight concentration samples generated from two extractions of wear particles from the same used oil sample. In two cases, the same sample was run more than once to test for repeatability of the DR ferrograph. Figure 3-3 is a graph of all of the "L" readings versus the metal concentration, in ppm, for readings up to 100. Readings larger than 100 are not recommended for precision work because the instrument responds non-linearly. Similarly, Figure 3-4 is a graph of all "S" readings versus metal concentration from the same data set. "X's" are plotted for data points of one extraction and subsequent dilutions, and "O's" are plotted for data points of one extraction and subsequent dilutions.

3.4 THE EFFECT OF PARTICLE SIZE DISTRIBUTION

The two graphs, for the "L" and "S" readings, are interdependent in that the abscissa, which is metal concentration, results from the total weight of all particles in each sample, whereas the DR readings are the result of light attenuation measurements at two cross sections along the DR tube corresponding to two different particle size ranges. For the relationship between DR readings and metal concentration to be linear, the proportion of large to small particles deposited from each sample at the location of the "L" and "S" light beams must be constant. This implicitly assumes that for the relationship to be linear, the dilutions must first be isodistributive; that is, the ratio of large to small particles in each sample must

remain constant with dilutions. Further, since data is presented for samples prepared from two extractions, the extraction and redispersion process must also reliably produce the same particle size distribution.

The straight lines of Figures 3-3 and 3-4 are the result of a linear regression analysis of all points for readings less than 100.

The correlation coefficients are r = 0.967 for the "L" readings and r = 0.991 for the "S" readings, and indicates, therefore, that the relationship between concentration and reading is linear. That both graphs have a slightly positive non-zero intercept on the ordinate axis seems to reflect physical reality. Filtered oil, as used for all dilutions, shows slightly positive readings of about 1 or 1.5, when run through the DR ferrograph.

Figures 3-5 and 3-6 show linear regression lines for the data points belonging to each extraction separately. Confidence in the extraction, redispersion, dilution process is built by the proximity of regression lines for one data set versus the other. The differences between data for the "X" set and the "O" set are most probably due to differences in the extraction technique, rather than to scatter from the dilution process or from the instrument itself.

Two other short tests were conducted to learn more about the particle size distribution of the samples. Firstly, one sample was subjected to prolonged agitation in the ultrasonic bath after which no change

in DR readings was obtained, indicating that the samples as tested were sufficiently deagglomerated and homogenized. Secondly, DR readings remained essentially unchanged for samples tested 2 weeks after the test series was conducted following heating and redispersion.

3.5 THE SEVERITY OF WEAR INDEX

Also included in Table 3-I is a calculation of the severity of wear index for each sample, as well as a normalized severity of wear index, formulated by the following reasoning. Consider a certain sample which results in some DR readings, D_L and D_S. If that sample had twice the concentration of particles, the readings should then be 2 D_L and 2 D_S, or if that sample had n times the concentration of particles, the readings should then be n D_L and n D_S, assuming that the densities were within the linear range of the ferrograph. For the first sample, the severity of wear index, I_S, equals $D_L^2 - D_S^2$. For the sample with n times the concentration of particles, I_S equals $(n\ D_L^2) - (n\ D_S^2) = n^2\ (D_L^2 - D_S^2)$.

3.6 MORE ON NORMALIZING FERROGRAPHIC DATA

This practice is consistent with a recommendation that was concurred upon by an ad hoc committee for ferrography standards, attended by Lt. Cmdr. Harold Martin, Office of Naval Research; Peter Senholzi, Naval Air Engineering Center; Richard Tessman, Fluid Power Research Center, Oklahoma State University; and Daniel Anderson, Foxboro Analytical; which will report to The Technical Cooperation Program (TTCP). Their recommendation, for ferrogram readings, is that

percent area covered readings be normalized to 1 ml of sample oil as follows:

$$A_N = \frac{A}{V_T \times \frac{V_O}{V_F + V_O} \times \frac{V_S}{V_S + V_D}} \qquad \text{(Eq.3-1)}$$

where

A_N - normalized ferrogram reading

A - reading taken from the ferrogram

V_O - volume of sample (subscript O for oil) pumped over ferrogram during preparation

V_F - volume of solvent in the sample bottle

V_T - volume of fluid pumped over the ferrogram

V_S - volume of sample oil used for dilution

V_D - volume of dilution oil (filtered oil) used for dilution.

It is recognized that $V_T = V_F + V_O$, reducing the formula to

$$A_N = \frac{A}{V_O \times \frac{V_S}{V_S + V_D}} \qquad \text{(Eq.3-2)}$$

but the longer form is presented for purposes of development of the formula. It is also recognized that the dilution factor n, discussed above, is

$$n = \frac{V_S + V_D}{V_S} \qquad \text{(Eq.3-3)}$$

which reduces equation 3-2 to

$$A_N = \frac{A}{V_O x \frac{V_S}{V_S + V_D}} = \frac{A}{V_O x \frac{1}{n}} = \frac{nA}{V_O}$$

and since V_O is typically 1 ml for the DR ferrograph, A_n equals nA, or if DR readings are used instead of ferrogram readings,

$$D_{\substack{\text{normalized} \\ (L \text{ or } S)}} = \frac{nD_{(L \text{ or } S)}}{V_O} .$$

Therefore, to relate I_S for the first sample to I_S for the later sample, I_S for the later sample must be divided by n^2, or concentration squared.

This has been done for the experimental data of Table 3-I, with the result that the normalized severity of wear index has, rather roughly, the same value for all the samples. Those data points furthest removed from the regression lines, such as the point for 1.7 ppm metal concentration, have the most divergent values for the normalized severity of wear index as would be expected. If points are chosen which are on the regression lines for both the large and small scale readings, the normalized severity of wear indexes will be equal.

From a practical standpoint, if a sample is diluted by a certain factor, the severity of wear index of the diluted sample may be made directly comparable to the severity of wear index of the undiluted sample by multiplying the severity of wear index of the diluted sample by the square of the dilution factor.

A good policy is to report percent area covered, multiplied by the dilution factor so that all readings are comparable, keeping in mind that readings should be a significant fraction of the linear range of the ferrograph in order to maintain accuracy. If the percent area covered are reported as n D_L and n D_S, and are used this way for the computation of I_S, I_S is normalized and should be comparable for various dilution factors.

3.7 SPECTROMETRIC VERSUS GRAVIMETRIC CALIBRATION

Table 3-II presents spectrometric data for the samples used to calibrate the DR ferrograph. The spectrometric concentrations reported are for parts per million Fe. Figure 3-7 graphically presents this data.

Figure 3-8 shows the lower range of this data which may be compared to Figure 3-3 because the scale is the same.

DR CALIBRATION DATA

Concentration (ppm)	DR READING "L"	DR READING "S"	$I_S = D_L^2 - D_S^2$	$\frac{I_S}{(\text{Conc.})^2}$	COMMENTS
0.34	5.0	2.8[3]	17	148	Same sample[2]
0.34	4.8	1.7[3]	20	174	
3.4	44.2	16.2	1691	146	
3.4	48.0	15.8	2054	177	Same sample[2]
3.4	47.8	15.0	2060	178	
9.7	126.3[1]	34.5	14760	157	These samples were all prepared by diluting a 49 ppm sample
5.0	90.5	20.3	7778	311	
1.7	37.4	9.8	1302	451	
0.73	12.7	4.5	141	265	
0.38	6.8	2.4[3]	41	280	These samples were all prepared by diluting a 70 ppm sample
0.91	8.5	3.5[3]	60	73	
3.6	45.8	13.5	1915	148	
3.8	56.8	14.6	3013	209	
5.8	77.3	25.4	5330	158	
12.7	126.5[1]	44.1	14060	87	

1 - These readings are greater than 100 and are above the recommended linear range of the Ferrograph. They have been excluded from the linear regression analysis.

2 - Oil taken from the same bottle.

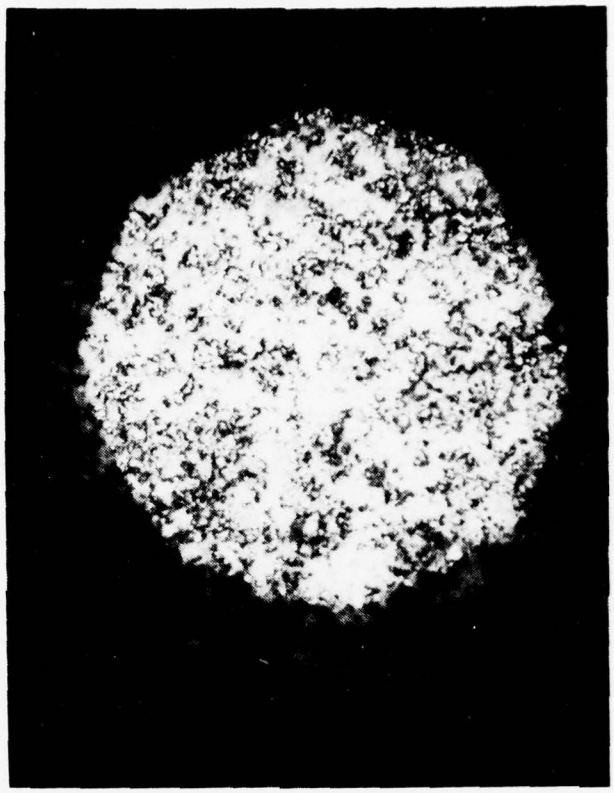
3 - Note that for the oil quantity chosen, these readings are a small percentage of full scale ($<$ 3.5%) and consequently the accuracy of these values is low when expressed as a fraction of the reading.

TABLE 3-I

SPECTROMETRIC DATA

Sample	Gravimetric Concentration	Spectrometric Concentration
A	0.34 ppm	1 ppm
B	1.7	2
C	0.38	1
D	3.8	4
E	3.4	4
F	0.73	1
G	9.7	8
H	5.0	3
I	5.8	4
J	0.91	1
K	12.7	12
L	3.6	3

TABLE 3-II



Nucleopore Filter With Wear Particles

X615. Weight gain of filter = 0.9 mg. Photo was taken with the reflected light source field diaphragm closed down. Therefore, the center portion of the photo shows metal particles reflecting light, whereas on the outer portion of the photo, which is illuminated only with transmitted light, the metal particles are black because they block the light from below.

FIGURE 3-1

K•E ... KEUFFEL & ESSER CO. MADE IN U.S.A.

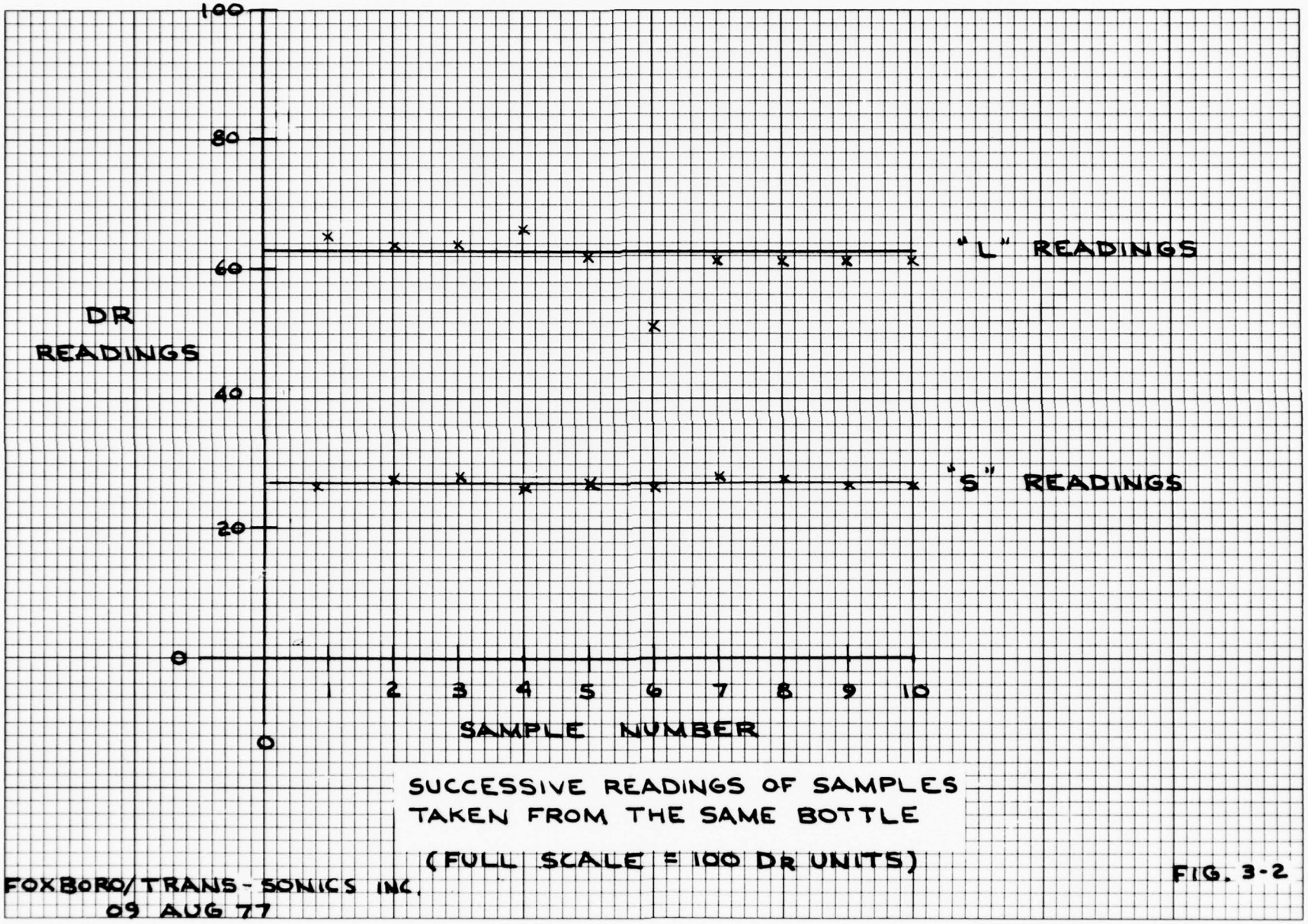


FIG. 3-2

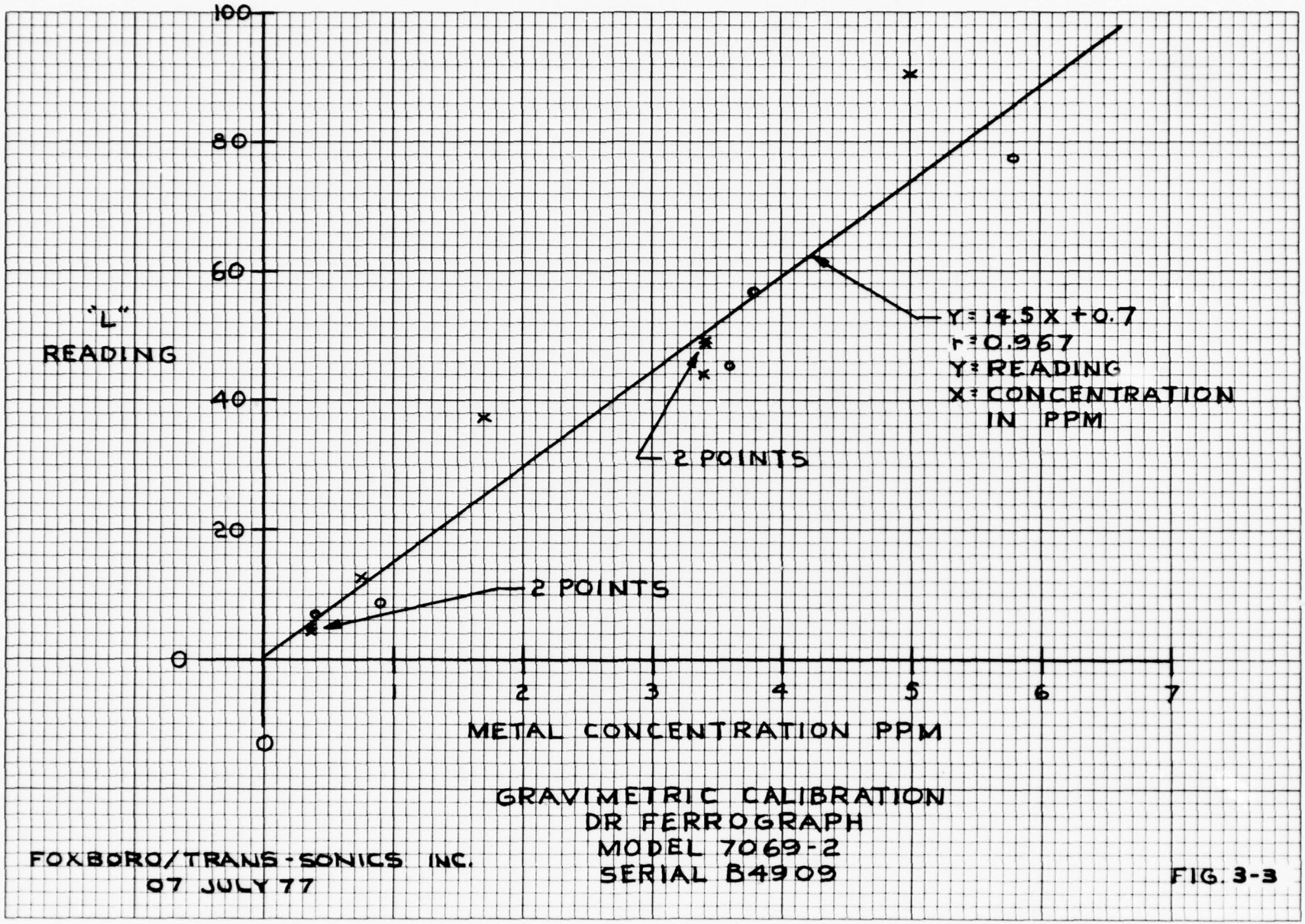

100
80
60
40
20
0
0
1
2
3
4
5
6
7
"L" READING
METAL CONCENTRATION PPM
Y = 14.5 X + 0.7
r = 0.967
Y = READING
X = CONCENTRATION IN PPM
2 POINTS
2 POINTS
GRAVIMETRIC CALIBRATION
DR FERROGRAPH
MODEL 7069-2
SERIAL B4909
FOXBORO/TRANS-SONICS INC.
07 JULY 77

FIG. 3-3

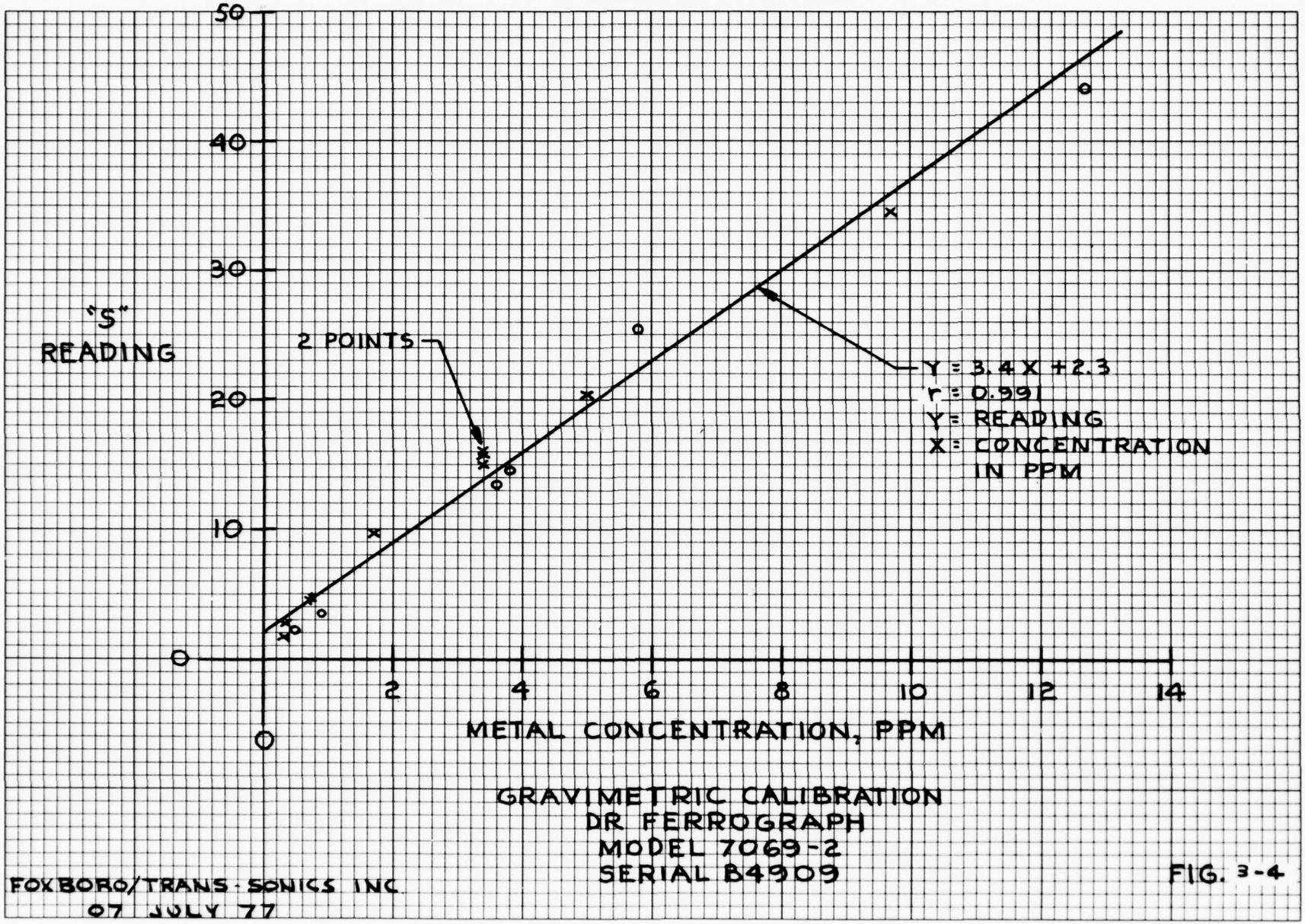

50
40
30
20
10
0
"S"
READING
2 POINTS
Y = 3.4X + 2.3
r = 0.991
Y = READING
X = CONCENTRATION
IN PPM
0
2
4
6
8
10
12
14
METAL CONCENTRATION, PPM
GRAVIMETRIC CALIBRATION
DR FERROGRAPH
MODEL 7069-2
SERIAL B4909
FOXBORO/TRANS-SONICS INC.
07 JULY 77

FIG. 3-4

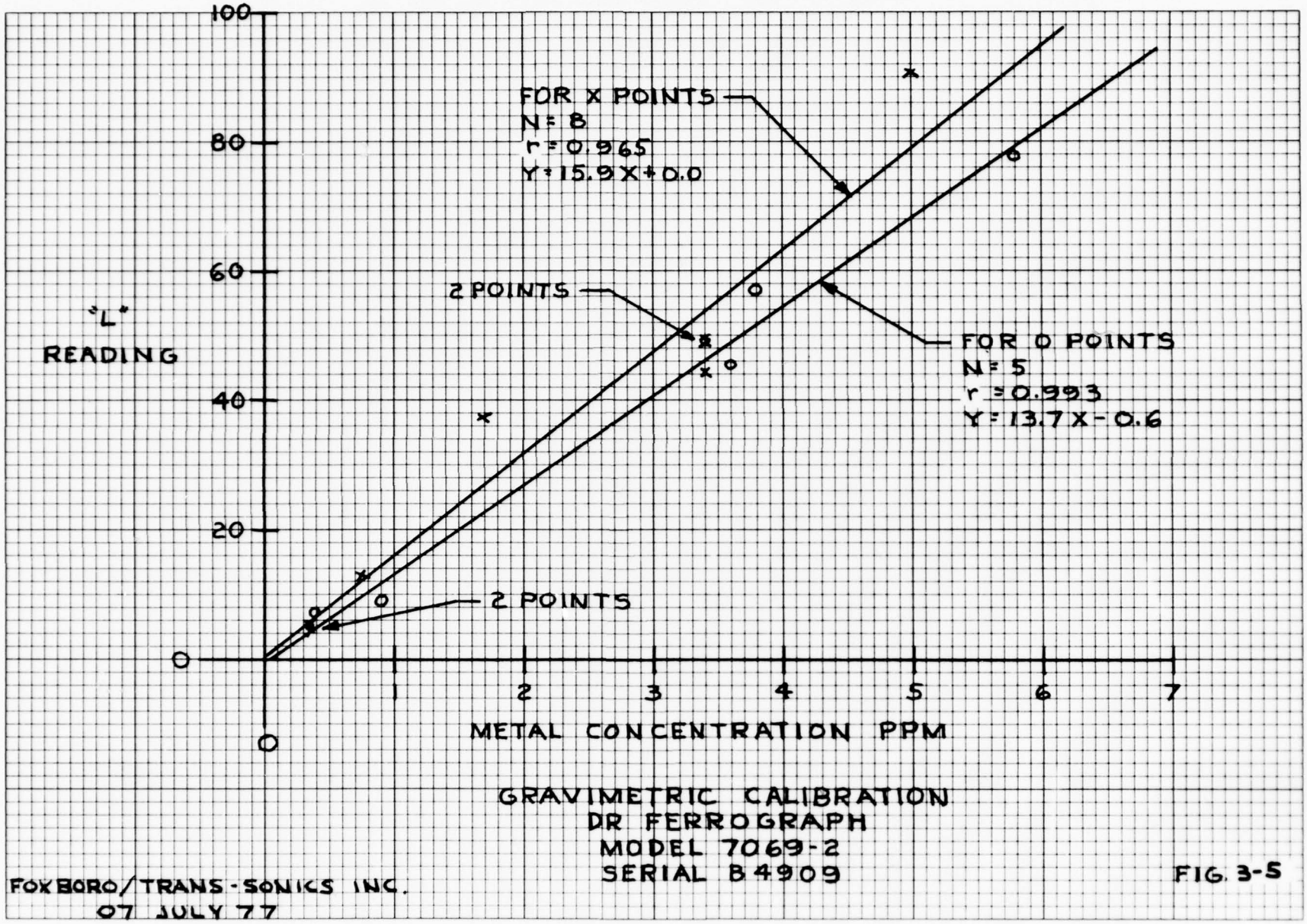

100
80
60
40
20
0
"L"
READING
FOR X POINTS
N = 8
r = 0.965
Y = 15.9X + 0.0
2 POINTS
FOR O POINTS
N = 5
r = 0.993
Y = 13.7X - 0.6
2 POINTS
0
1
2
3
4
5
6
7
METAL CONCENTRATION PPM
GRAVIMETRIC CALIBRATION
DR FERROGRAPH
MODEL 7069-2
SERIAL B4909
FOXBORO/TRANS-SONICS INC.
07 JULY 77

FIG. 3-5

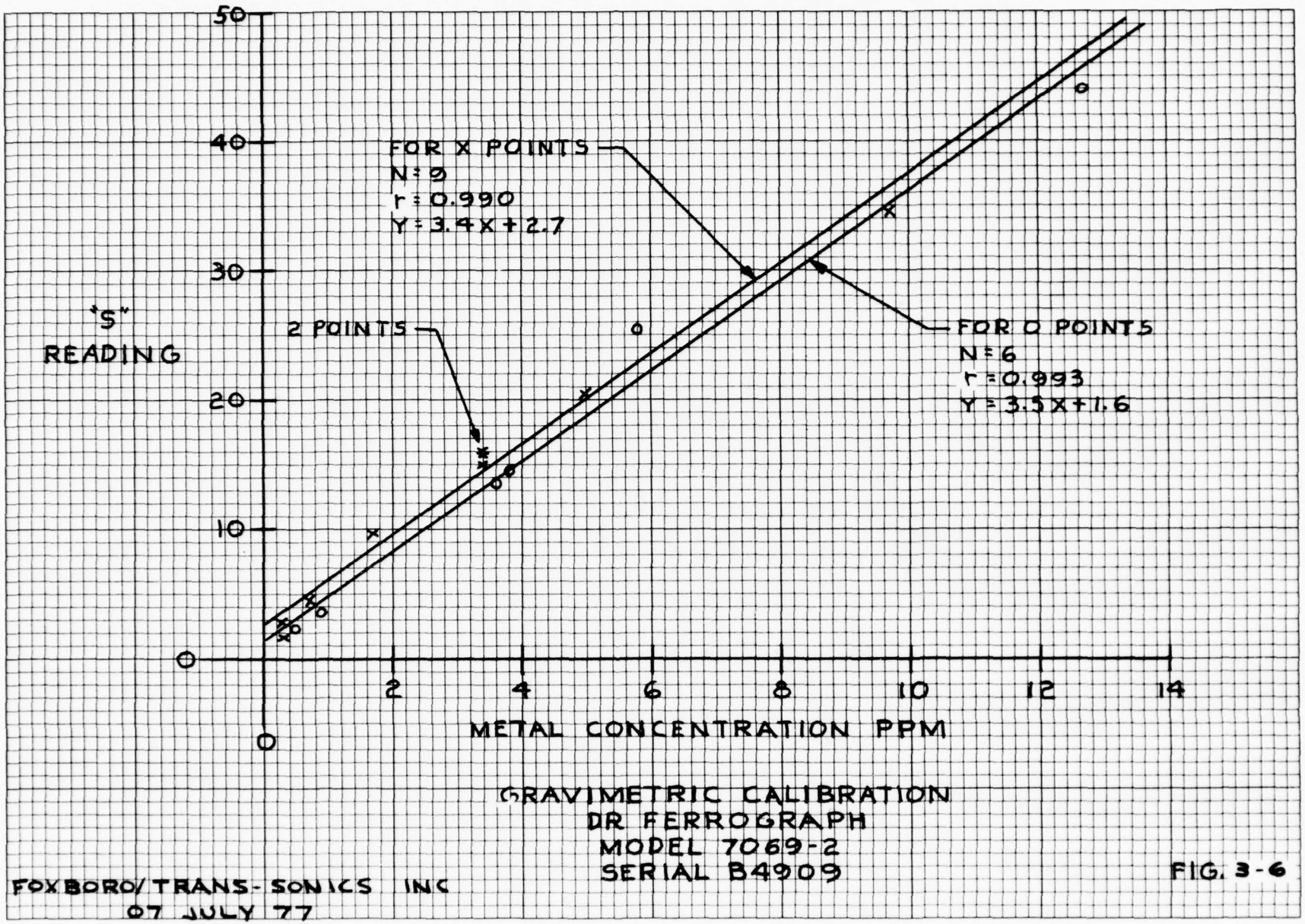
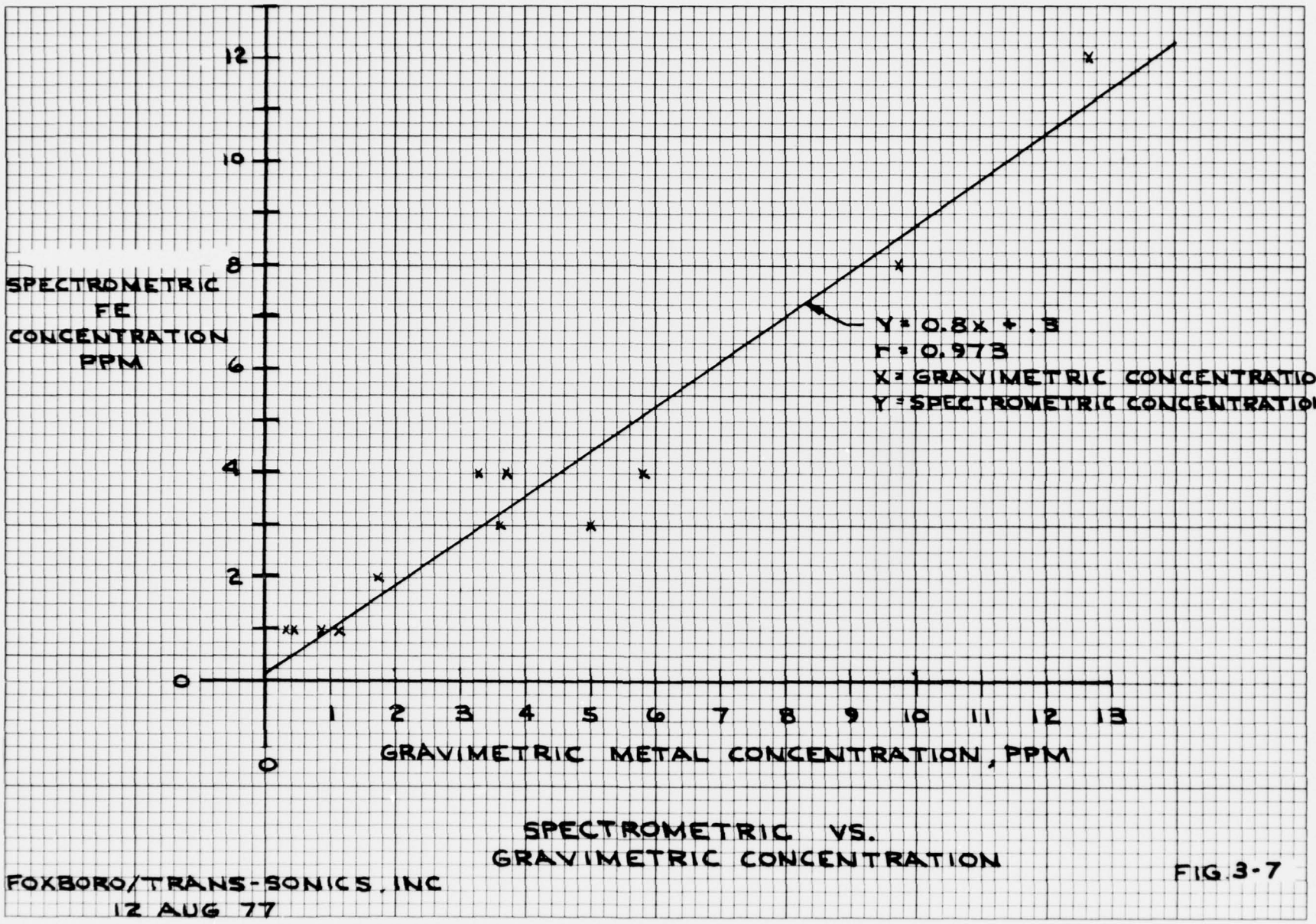

50
40
30
20
10
0
"S"
READING
FOR X POINTS
N=9
r=0.990
Y=3.4X+2.7
2 POINTS
FOR O POINTS
N=6
r=0.993
Y=3.5X+1.6
0
2
4
6
8
10
12
14
METAL CONCENTRATION PPM
GRAVIMETRIC CALIBRATION
DR FERROGRAPH
MODEL 7069-2
SERIAL B4909
FOXBORO/TRANS-SONICS INC
07 JULY 77

FIG. 3-6

K·E 10 X 10 TO THE INCH 7 X 10 INCHES
KEUFFEL & ESSER CO. MADE IN U.S.A.



SPECTROMETRIC VS.
GRAVIMETRIC CONCENTRATION

FIG. 3-7

FOXBORO/TRANS-SONICS, INC
12 AUG 77

K•E 10 T INCH .0 INCH
KEUFFEL & ESSER CO. MADE IN U.S.A.

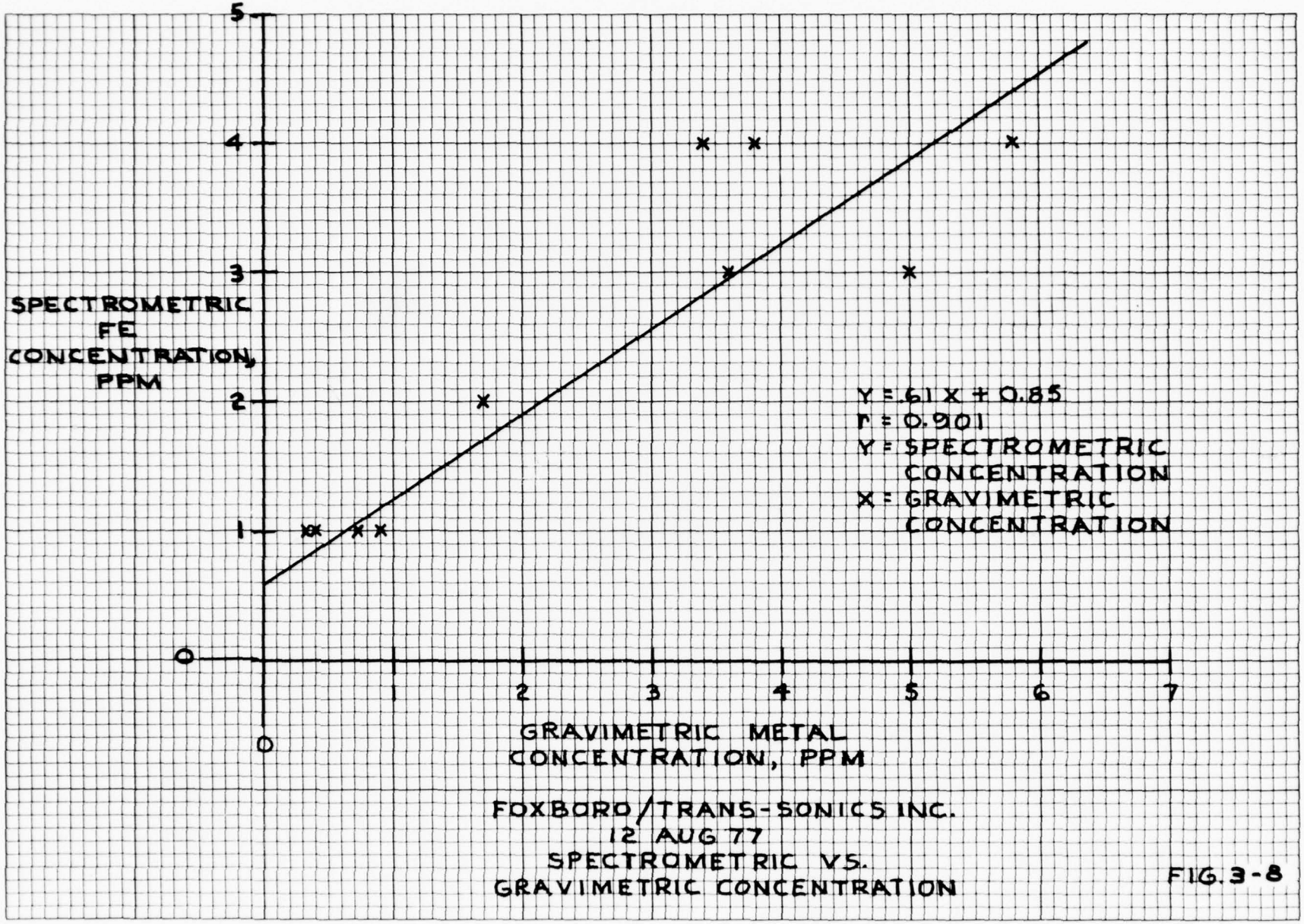


FIG. 3-8

4. EQUILIBRIUM PARTICLE CONCENTRATION

Experience with ferrographic data for various different machines resulted in the observation that, after break-in, particle concentration remains at about the same level from sample to sample until the machine begins to fail if sampling is done in a consistent manner and if machine operating conditions, such as speed, temperature, load, etc., are held constant. It was also observed for both jet engines and marine diesel engines that the throttle setting very much affected the number and size distribution of wear particles the engine produced and that these changes were evident in the oil coming from the engine a short time after a throttle adjustment was made. This indicated that the average lifetime of a particle in an oil system was not that long.

These observations led to the formulation of a simple mathematical model to better explain the behavior of particles in the oil of an engine. A geometric series is obtained, which is summed, and a formula is given for calculating the time to reach equilibrium for various operating conditions

Given an operating engine with an oil volume, V cc, which circulates the oil at a rate of F cc/sec, a cycle or "residence" time, T sec, of the oil though the system as $T = \frac{V}{F}$ sec, can be defined.

Let us assume that in this residence time, X particles/oil cycle are produced and in the same time $-a_i X$ of these particles are destroyed either by filtering or by other mechanisms. The i subscript refers to the particle diameter with the understanding that the rate a is a function of the particle size and lies in the range

$$1 \geq a_i \geq 0$$

The assumption that particle removal rate, a, is proportional to the number of particles present, X, is justified if the particle dispersion is sufficiently dilute; that is, if particles do not interact with other particles to form agglomerates or that particles are mutually repelled. Typical particle removal mechanisms such as interception by the fiber of a filter, impaction, wherein a particle cannot follow the flow streamlines around a sharp turn and collides with a collecting surface, sedimentation, such as occurs in a oil sump, magnetic separation as may occur in electric machinery, are all proportional to the number concentration of particles dispersed in a viscous fluid. Clearly, these removal mechanisms are a strong function of particle size, density, and shape.

To set up the basic equations, it is instructive to follow the history of the engine from when the oil is changed.

1st cycle - In the first cycle, X particles are produced, and $a_i X$ removed, leaving a number of particles N of diameter i at the end of this cycle equal to

$$N(a_i,1) = X(1 - a_i) \tag{1}$$

2nd cycle - A further $a_i X (1 - a_i)$ particles are removed from the particles remaining from the first cycle, leaving $(1 - a_i) X (1 - a_i)$ and we have a new contribution $X (1 - a_i)$ from this cycle

$$N(a_i,2) = X(1 - a_i) + X(1 - a_i)^2 \tag{2}$$

3rd cycle - the term describing the particles remaining from the first cycle becomes $X\ (1 - a_i)^3$, the particles from the second cycle are reduced to $X\ (1 - a_i)^2$, and we have a contribution $X\ (1 - a_i)$ from the third cycle, giving

$$N\ (a_i,3) = X\ (1 - a_i) + X\ (1 - a_i)^2 + X\ (1 - a_i)^3 \qquad (3)$$

n cycles - A pattern is seen to emerge, and for n cycles, we have

$$N\ (a_i,n) = X\ (1 - a_i) + X\ (1 - a_i)^2 + \ldots . X\ (1 - a_i)^n \qquad (4)$$

Let $1 - a_i = y$

We need the sum of the series

$$N\ (a_i,n) = X\left[y + y^2 + y^3 + \ldots . y^n\right] = X \sum_{r\ =\ 1}^{n} y^r \qquad (5)$$

But we know that

$$\sum_{r\ =\ 0}^{n} y^r = \frac{1 - y^n}{1 - y} = 1 + \sum_{r\ =\ 1}^{n} y^r \qquad (6)$$

Therefore,

$$N\ (a_i,n) = X\left[\frac{1 - y^n}{1 - y} - 1\right]$$

$$= X\left[\frac{(1 - a_i) - (1 - a_i)^n}{a_i}\right] \qquad (7)$$

As $n \longrightarrow \infty$ it may be easily shown that $(1 - a_i)^n \longrightarrow 0$ and we have the simple result that at equilibrium

$$\boxed{N(a_i, \infty) = X\left(\frac{1 - a_i}{a_i}\right)} \tag{8}$$

Of most interest is the number of residence cycles which must occur before we are some infintessimal distance from the equilibrium or infinite sum value. Let us define a quantity β where $\beta << 1$ such that after R cycles we have reached a situation

$$\frac{N(a_i, R)}{N(a_i, \beta)} \geq 1 - \beta \tag{9}$$

We need to evaluate this equation for R when a_i, β are specified. Using equations 8 and 9, we can obtain

$$(1 - a_i)^{R-1} \geq \beta \tag{10}$$

Taking logarithms

$$R \geq 1 + \frac{\ell n \ \beta}{\ell n \ (1 - a_i)} \tag{11}$$

R is taken as the smallest integer value so as to make equation 11 valid.

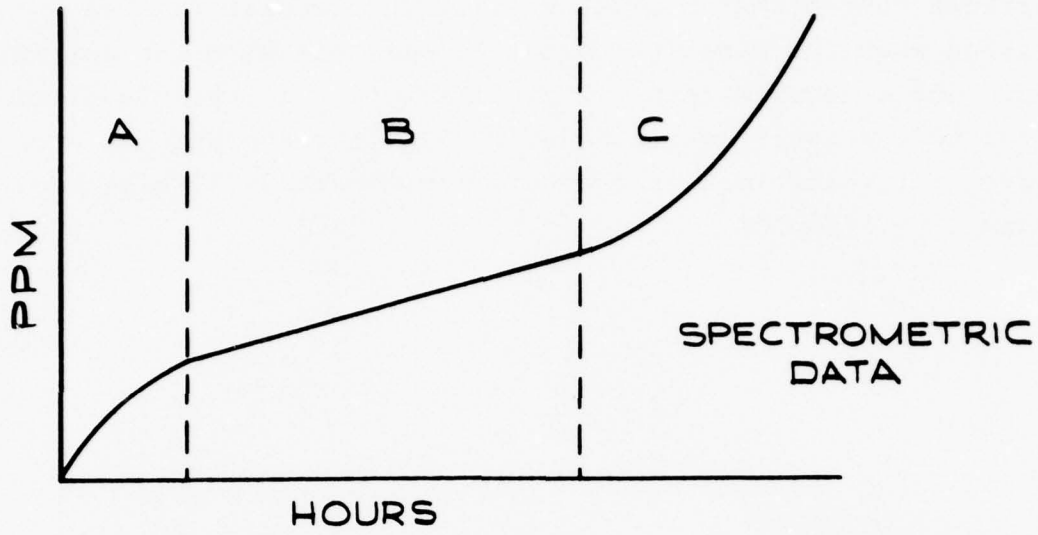
In Table 4-I values of the quantity N (a,n) are given for various values of n and a, and it is seen as expected that this series is less convergent the smaller a is. At the bottom of Table 4-I, the values of N (a,β) are listed for the

various a's used in Table 4-I and also the number of cycles, R, needed for the particle concentration to reach 99% ($\beta = 0.01$) of its equilibrium value.

This is of practical value because it allows an estimate for how long a machine should be operating before a representative (of equilibrium conditions) sample is taken. For a machine with small oil capacity, high flowrate, and efficient filtration, the time will be short, whereas longer time is required for unfiltered systems with greater oil capacity and lower flowrate. If the concentration of small particles is of concern (which usually is not the case for engine condition monitoring), greater time to equilibrium is predicted because removal mechanisms (filtration, sedimentation, etc.) are less efficient for small particles.

Also of practical value is the fact that particle concentration is demonstrated to reach a ceiling value based on first principles, a result often not intuitively obvious when describing sampling strategy for ferrography.

This exercise points to a fundamental difference between spectrometric and ferrographic data acquired from the same machine. Figure 4-1 shows how spectrometer readings and ferrograph readings vary as a machine runs from break-in to normal wear to abnormal wear. The ferrograph readings maintain a dynamic equilibrium during normal wear, but the spectrometer readings increase linearly. This is consistant with the foregoing particle equilibrium concentration model when it is considered that the spectrometer reading integrates the metal content from the molecular level to the largest particle size that is vaporized by the flame. Very fine metal particles have decreasing removal efficiency, (a_i) by the mechanisms assumed in the equilibrium



A = BREAK-IN WEAR
B = NORMAL WEAR
C = ABNORMAL WEAR

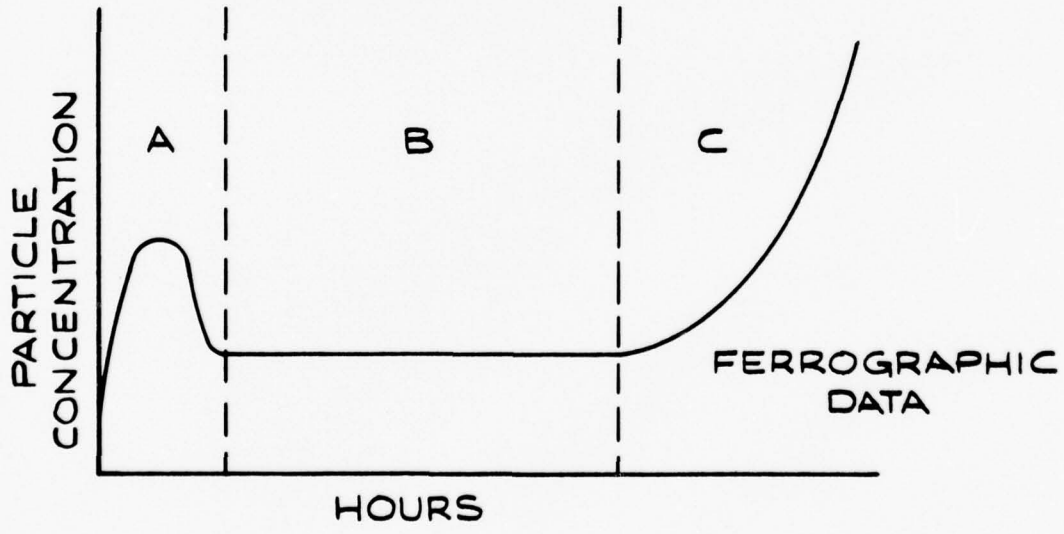


FIGURE 4-1
COMPARISON OF IDEALIZED DATA

particle concentration model until the molecular size is reached when the dissolved metal becomes one with the carrier fluid and a_i equals zero. The contribution of the dissolved metal to the spectrometer reading will increase but the much larger particles, measured by the ferrograph, will stay in dynamic equilibrium.

TABLE 4-1, VALUES OF N (a,n)

n	a .9	a .8	a .5	a .1	a .05	a .01	a .001
1	.1	.2	.5	.9	.95	.99	.999
2	.11	.24	.75	1.71	1.8525	1.9701	1.997
3	.111	.248	.875	2.479	2.7099	2.9406	
4	.1111	.2496		3.095	3.5244	3.9010	
5		.24992	.96875	3.686	4.2982	4.8520	4.985
7						6.7255	
10		.2499997	.99902	5.862	7.624	9.4662	9.945
15			.999969	7.147		13.8542	
20				7.906	12.188	18.0272	19.791
25				8.354			
30				8.619		25.7677	29.539
40							
50				8.954	17.538	39.1044	
70							
100				8.9998	18.8875	62.7628	95
150							139
200						85.736	181
300						94.145	259
400						97.222	328
500						98.349	398
600							451
700						98.9128	503
800							550
900							593
1000							631
1200							698
1600							797
2000							964
2200							888
.							
.							
.							
.							
.							
∞	.111111	.25	1.0	9.0	19.0	99.0	999
3	.99(.11111)						
4		.99(0.25)					
8			.99(1.0)				
45				.99(9.0)			
91					.99(19.0)		
460						.99(99.0)	
4604							.99(999.)

5. PARTICLE FILTER STUDY

During the last several years, jet engines and other machines have been built that have oil filters that effectively remove all particles larger than 3 μm in major dimension. These filters also capture a significant fraction of particles smaller than 3 μm. Consequently, the particle concentration in the oil is so low that a 3 cc sample (the usual sample volume) will not produce a ferrogram with enough particles for an analysis. It is predicted that many more new machines will have high quality oil filtration. Therefore, work was undertaken to develop a sampling filter which could be plumbed into a machine's oil system to capture particles for subsequent ferrographic analysis. Work was only of a preliminary nature and a sampling filter design remains to be developed.

Figure 5-1 shows a schematic diagram of the filter test rig assembled for the purpose of evaluating various filter media. The test system allows measurement of pressure drop across the test filter, temperature of the oil (thermometer in tank), and oil flowrate (measured by collection at the secondary drain). Measurement of these three variables as well as careful weighing of the filter, wash, and wash after ultrasonic agitation allows determination of the following:

(1) Efficiency and size selectivity of various media (ferrograms made before and after test filter).
(2) Clogging characteristics of various media (load vs. ΔP and load vs. flowrate).
(3) Relationship of flowrate, temperature, viscosity, and pressure drop.
(4) Which filter media wear particles may be recovered from.

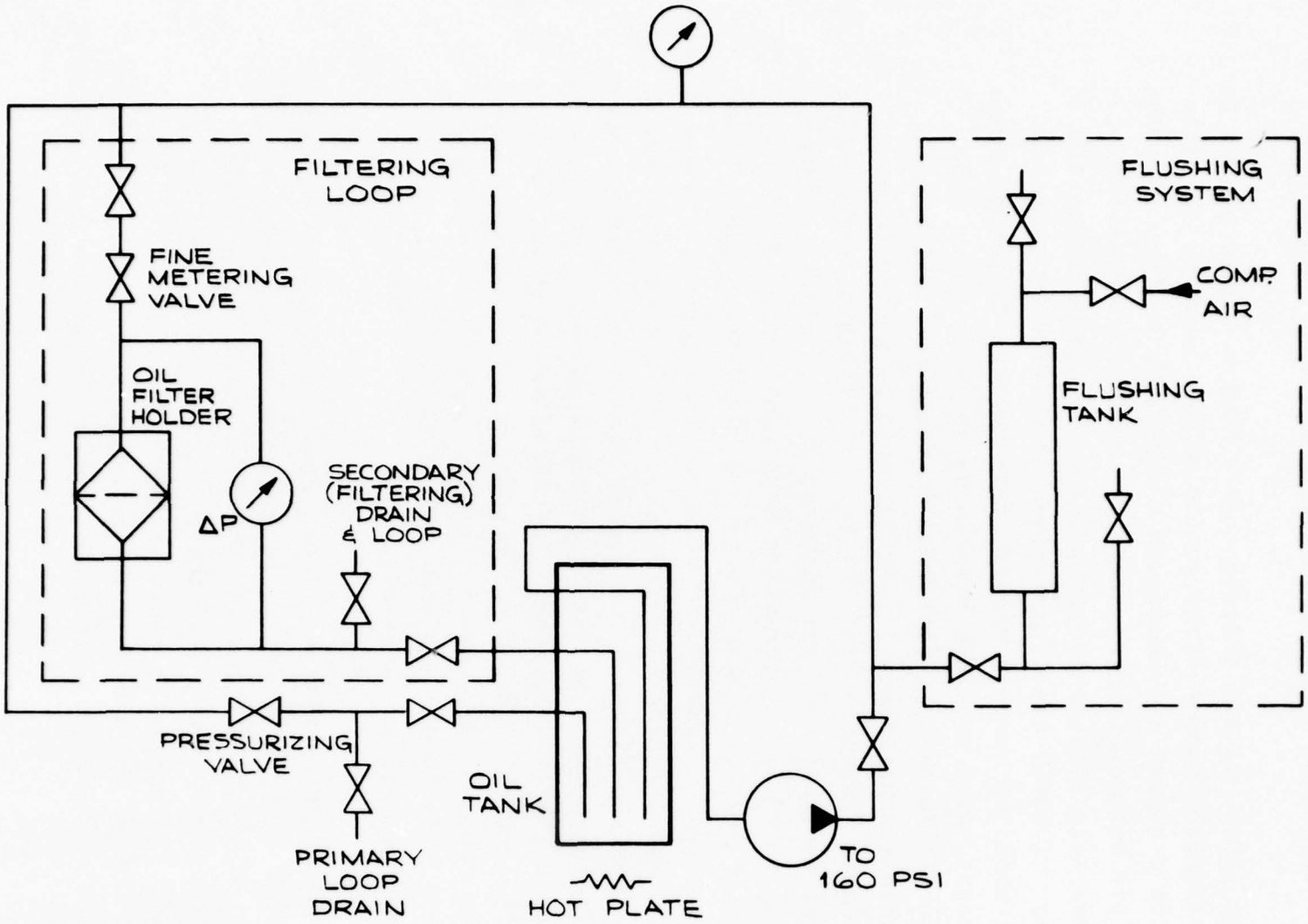


FIGURE 5-1

WEAR PARTICLE FILTER TEST RIG

(5) Determine temperature limit of various media.

At the onset, it was decided that a coarse filter should be investigated because large particles are those most indicative of a severe wear mode and a coarse filter could filter more oil before becoming clogged. Membrane and fibrous filters were thus immediately eliminated from contention because of their small pore size. Samples of stainless steel mesh, of various weaves, from several different manufacturers, with openings down to as small as 10 μm were obtained. Tests were performed to establish that several of these stainless steel filters could be washed to an acceptable "particle free" level. The filters, after being punched out to the proper diameter for the filter holder, were agitated in an ultrasonic bath containing 50% filtered synthetic jet oil (MIL-L-23699) and 50% chlorinated hydrocarbon solvent. Ferrograms prepared from the wash showed quite a few large metal particles identified as stainless steel from the filter. The second wash resulted in a much cleaner ferrogram, and the ferrogram from the third wash was indistinguishable from a ferrogram prepared only from blank materials. This demonstrated that the stainless steel filters could be acceptably cleaned. However, the cleaning process, which would add some to the final cost of this sampling method, is necessary.

Tests of 10 μm opening stainless steel mesh on the aforementioned test rig resulted in a disappointing size selectivity. However, examination of the cleaned filter under the microscope showed that the particles were effectively removed. It was anticipated that the size cut of the filter around 10 μm, measured as the major particle dimension, would not be perfect, but the ferrograms prepared from test

10 μm filters showed an abundance of small particles, down to the lower limit of optical microscopical resolution. These results were obtained from rather lightly loaded filters, judging from their appearance when they were removed from the filter holder prior to washing. It must be assumed that quite a few fine particles are captured by the mesh itself since the percent open area for very fine wire mesh filters is around 30 to 40%. As a cake is formed by the filtrate the percent open area will decrease and the collection efficiency for all particle sizes will increase. Therefore, it does not appear that a fine wire mesh will be able to provide the size selectivity originally intended without some control over sample volume.

Tests were also performed with 15 μm and 20 μm wire mesh filters with the result that fewer small particles were captured and a greater oil volume (the particle concentration in the oil was about the same for these tests) could be filtered as the mesh size increased. Nevertheless, the number of small particles was substantial.

As shown by the model for equilibrium particle concentration in engine oil, part 4 of this report, the particles in the oil tank of systems with high efficiency filters are of recent generation. The probability, P, that a particle of size i remains after n cycles of all the oil through a machine with filtration efficiency a_i, is

$$P = (1 - a_i)^n$$

So, for a particle of 2.0 μm major dimension which may have a 50% chance of being caught by a 3.0 μm filter, the probability that is survives one oil cycle is

$$P = (1 - 0.5)^1 = 0.5$$

the probability that it survives two oil cycles is

$$P = (1 - 0.5)^2 = (0.5)^2 = 0.25$$

the probability that it survives 4 cycles is

$$P = (1 - 0.5)^4 = (0.5)^4 = 0.0625$$

and after 10 cycles the probability is only

$$P - (1. - 0.5)^{10} = 0.000976 \cong .001$$

or about 1 chance in a thousand. Table 5-I is presented, which gives the probability of a particle surviving after the oil has been recirculated a given number of times (n) if it has a certain capture efficiency (a).

Examination of this table indicates that with even poor capture efficiency, say 1%, that after 500 cycles less than 1%, (.7% from the table) of the original particles of that size will remain. Some military jet engines circulate the total amount of oil about 6 times a minute. This means that after only

$$\frac{500 \text{ cycles}}{6 \text{ cycles/min} \times 60 \text{ min/hr}} = 1.38 \text{ hours of}$$

operation particles of 1% removal efficiency will have less than a 1% chance of remaining. As mentioned previously, the particles indicative of a severe wear mode are the larger particles which, pesumably, will have greater removal efficiencies than 1%. Therefore, the particles precipitated

on a ferrogram which are of greatest interest have been very recently generated. The sampling filter has been investigated in order to review the operating history of an engine over some reasonable time period, during which time the engine would operate at speeds and loads that might be expected to stress the engine.

Other solutions besides a sampling filter are possible. One is to sample at high speed and load, which is practical for diesel engines and land based equipment but not for aircraft.

It appears important to continue work on a means of obtaining a representative sample from an extended operating time period. Anticipated difficulties, aside from the poor size selectivity of wire mesh filters, are the associated problems of measuring flow rate and volume (flow rate x time).

PROBABILITY OF SURVIVING n OIL CYCLES
WITH CAPTURE EFFICIENCY, a, PER CYCLE

Cycles	CAPTURE EFFICIENCY a					
n	90%	50%	10%	1%	.1%	.01%
1	.1	.5	.9	.99	.999	.9999
2	.01	.25	.81	.98	.998	.9998
5	.00001	.031	.59	.95	.995	.9995
10	1×10^{-10}	0.8×10^{-4}	.35	.90	.990	.9990
20	1×10^{-20}	0.5×10^{-7}	.12	.81	.980	.9980
50	1×10^{-50}	8.8×10^{-16}	.005	.61	.951	.9950
100			2.6×10^{-5}	.37	.905	.990
500			1.3×10^{-23}	.007	.61	.951
1000				4.3×10^{-5}	.37	.905
5000					.007	.61
10000						.37
50000						.007

TABLE 5-I

6. SPLINE WORK

Professor Nam Suh and Dr. Nannaji Saka of the Mechanical Engineering Department at the Massachusetts Institute of Technology have been investigating soft metal coatings toward prolonging aircraft spline life before failure. Their work has been funded by the Office of Naval Research, Contract No. N00014-76-C-0068. Foxboro Analytical, under its contract with the Office of Naval Research, has been supporting the efforts of Nam Suh by analyzing tested splines. The spline program is briefly summarized here to give this report some perspective. Full details will be available in a forthcoming report by Suh, et al.

Aircraft splines were coated with varying thicknesses (0.1 μm, 1.0 μm, and 10 μm) of soft (softer than the spline steel) metal coatings. Initially, gold, silver, nickel, and cadmium were tried at the thicknesses cited above. These coated splines were then tested by the Naval Air Development Center, Warminster, Pennsylvania, using a spline testing machine. The test splines are purposely misaligned and subjected to low amplitude, high frequency loading. The splines are greased with MIL-G-81322B before the start of the test. The test is ended when the splines have worm .381 mm (.015 inch) as measured by a displacement transducer.

The following is a copy of a report prepared at Foxboro Analytical which was circulated to the principals involved in this program. Unfortunately, cost considerations do not allow color reproduction of the report.

Foxboro Analytical
A Division of The Foxboro Company
Burlington Center

78 Blanchard Road
P.O. Box 435
Burlington, MA 01803
Tel: (617) 272-1000
Telex: 94-9402
TWX: 710-332-1635

FERROGRAPHIC ANALYSIS
OF
SPLINE WEAR DEBRIS

12 OCTOBER 1978

FOXBORO

The first six splines tested by the Naval Air Development Center in Warminster, Pennsylvania for Nam Suh's group, resulted in the data shown in Figure 1. The wear test equipment allows measurement of the amount of wear in thousandths of an inch, for each spline as a function of time. Five splines were tested to failure, but for one spline, number 51, the test machine broke down before the spline showed any measurable wear. This was fortuitous since a spline was made available for Ferrographic analysis before the failure mode took over.

The splines were prepared for analysis by first washing them in 10 ml of 50% MIL-L-23699 jet oil and 50% hexane using an ultrasonic bath. Toothpicks were used to pry grease loose from between spline teeth. The grease was quite dry and was well adhered to the spline. Ultransoic agitation broke up the dried grease freeing the metal wear particles. The resulting wash was then diluted by as much as 2000:1 to obtain Ferrograms with the proper number of particles for comfortable microscopic examination.

Ferrographic analysis revealed that the wear particles for all the failed splines are similar. The particles are equiaxed (chunks), all large compared to benign wear debris for sliding or rolling contacts, and are characterized by surface oxidation. In contrast, the particles for the unfailed spline, number 51, are flat and are composed of free metal. Some chunks are also present, suggesting that the time to failure would not have been long.

For this report, two Ferrograms were chosen for photomicroscopy: spline #56, the wash from which was diluted 867:1 and spline #51, the wash from which was diluted 739:1. The dilution factors are reported with high accuracy because a precision balance was used to make them, even though, for this analysis, great accuracy is not necessary.

Photo F2117-1 is an overall entry view at low magnification for the failed spline and F2104-1 is a comparable view for the unfailed spline. Since the particle deposits are about equally heavy, the number of particles in the wash from the failed spline is about 100 times as many.

Photo F2117-2 shows some spline wear particles just down from the entry region of the Ferrogram. Their chunky morphology is apparent when one notices that smaller particles deposited nearer the glass substrate are out of focus. F2117-3 shows some of the larger particles deposited at the entry. F2117-4 is a 1000 times magnification view of one of these particles, close scrutiny of which reveals spots of blue temper color attesting to high temperature during its generation. These spots are more easily seen when actually viewing through the microscope.

Photo F2117-5 shows a chunk that has a bit of gold plating stuck to one side. F2117-6 shows this particle in greater detail; notice that several cracks, running in different directions, may be seen in the gold.

F2117-7 was taken at the 50 mm position of the Ferrogram where the largest particles are unable to reach. The morphology of these particles appears similar to that for the large particles.

The non-metallic crystalline nature of the particle surfaces are demonstrated using fully polarized reflected light in F2117-8. These particles may be described as dark metallo-oxide particles, although when viewed in white reflected light, they are not as dark as oxide coated particles often seen on Ferrograms prepared from internal combustion engine oil samples. The intentisy of the depolarized light scattered from the particles in F2117-8 was not great; an exposure time of 5 minutes was required whereas the other 400X photos were typically shot at 1/4 second. F2117-8 may be recognized as almost the same view as F2117-2.

F2104-1, the low magnification entry view for the unfailed spline, shows that in addition to flat particles, quite a few spline wear chunks are present. This allows speculation that the failure mode, which proceeds rapdily once initiated as shown on Figure 1, may not be far off. Further work needs to be done to validate this prediction.

F2104-2 shows, at high magnification, one of the bright, flat wear particles typical of this Ferrogram. F2104-3 shows more flat wear particles at intermediate magnification. This view may be recognized as the central portion of the overall entry view, F2104-1. F2104-4, taken using bichromatic light (red reflected and green transmitted light), demonstrates the high reflectivity of these particles.

F2104-5 is the same view as F2104-3 and F2104-4 except that the focal plane has been raised 11 μm, the thickness of this spline wear chunk. This particle is about 30 μm in major dimension.

F2104-6 shows one of the several gold particles deposited on this Ferrogram.

FIGURE 1 – DATA FOR TEST SPLINES

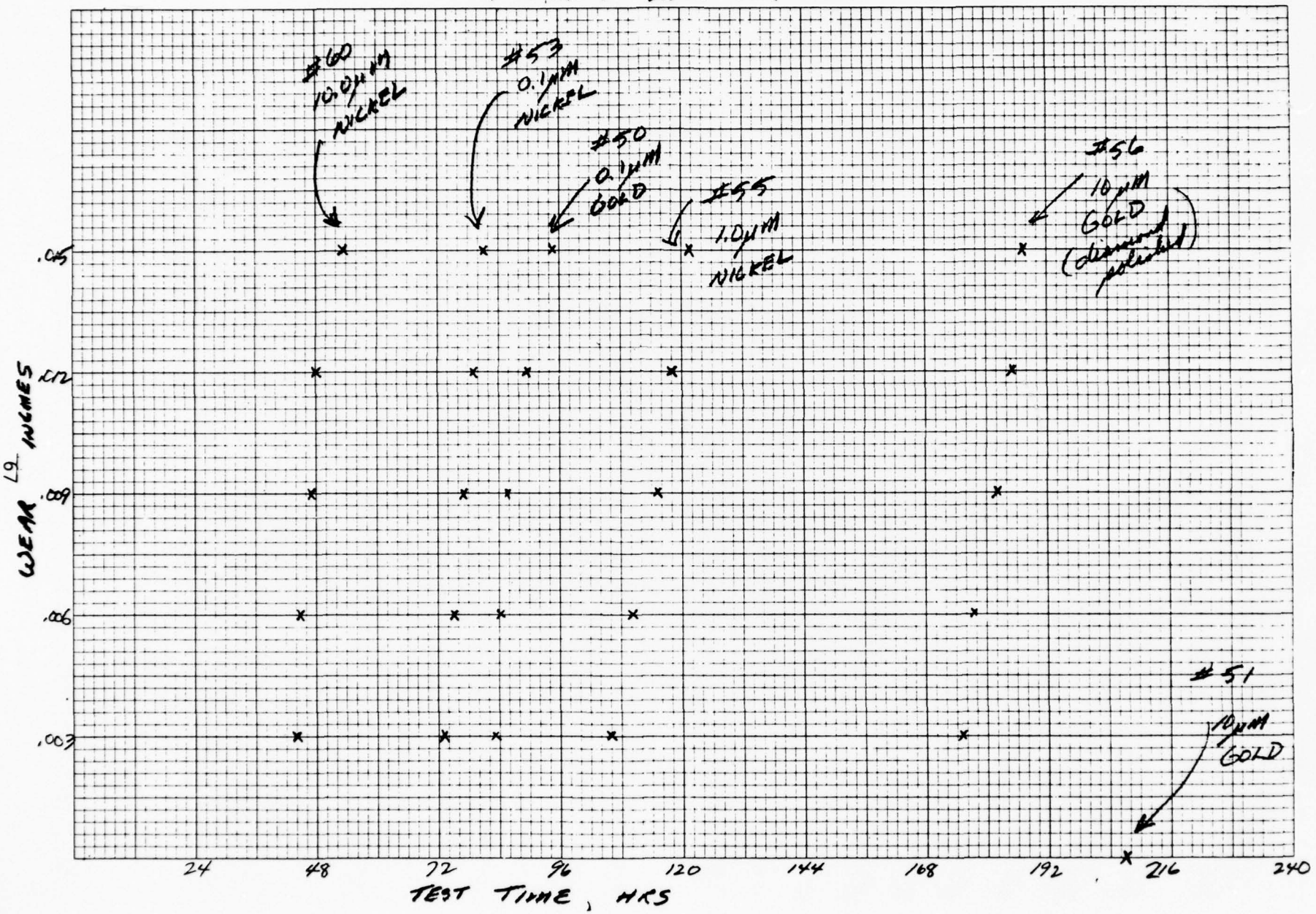


PHOTO NO. F2117-1 DATE 9/22/78

MAGNIFICATION: 100X

LOCATION ON FERROGRAM: Entry

SAMPLE IDENTIFICATION:

Spline #56

OPERATING HISTORY:

Tested to failure.

REMARKS:

low magnification view of the entry deposit

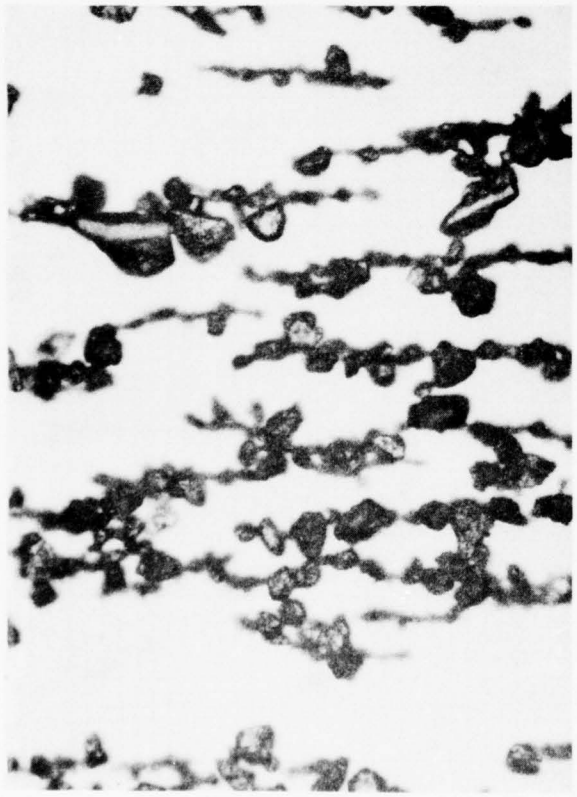


PHOTO NO. F2117-2 DATE 9/22/78

MAGNIFICATION: 400X

LOCATION ON FERROGRAM: 52.5 mm

SAMPLE IDENTIFICATION:

Spline #56

OPERATING HISTORY:

Tested to failure.

REMARKS:

a higher magnification view of the wear debris just down from the entry

PHOTO NO. F2117-3 DATE 9/22/78

MAGNIFICATION: 400X

LOCATION ON FERROGRAM: Entry

SAMPLE IDENTIFICATION:

Spline #56

OPERATING HISTORY:

Tested to failure.

REMARKS:

Particles on right central portio. of F2117-1. Notice that the varying thickness of these chunks causes some to be out of focus.

PHOTO NO. F2117-4 DATE 9/22/78

MAGNIFICATION: 1000X

LOCATION ON FERROGRAM: Entry

SAMPLE IDENTIFICATION:

Spline #56

OPERATING HISTORY:

Tested to failure.

REMARKS:

High magnification view of large particle seen in F2117-3 above. Close scrutiny reveals spots of blue temper color on the particle surface

PHOTO NO. F2117-5 DATE 9/22/78

MAGNIFICATION: 400X

LOCATION ON FERROGRAM: 54.4 mm

SAMPLE IDENTIFICATION:

Spline #56

OPERATING HISTORY:

Tested to failure.

REMARKS:

Dark metallo-oxide chunk coated with some gold.

PHOTO NO. F2117-6 DATE 9/22/78

MAGNIFICATION: 1000X

LOCATION ON FERROGRAM: 54.4 mm

SAMPLE IDENTIFICATION:

Spline #56

OPERATING HISTORY:

Tested to failure.

REMARKS:

Same particle as in F2117-5 above, at high magnification. Gold is cracked in several places.

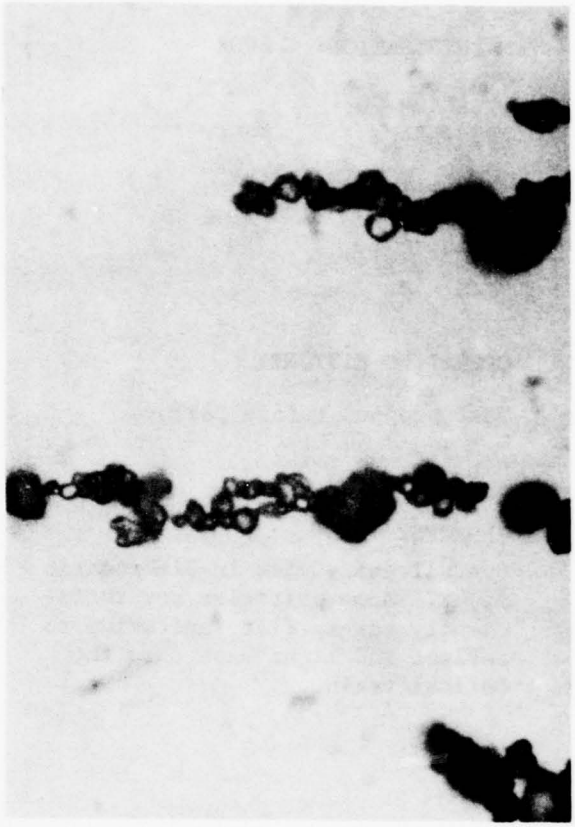


PHOTO NO. F2117-7 DATE 9/22/78

MAGNIFICATION: 1000X

LOCATION ON FERROGRAM: 50 mm

SAMPLE IDENTIFICATION:

Spline #56

OPERATING HISTORY:

Tested to failure.

REMARKS:

Smaller particles which penetrated to the 50 mm position have the same shape and surface features as the larger particles.

PHOTO NO. F2117-8 DATE 9/22/78

MAGNIFICATION: 400X

LOCATION ON FERROGRAM: 52.4 mm

SAMPLE IDENTIFICATION:

Spline #56

OPERATING HISTORY:

Tested to failure.

REMARKS:

Polarized reflected light demonstrates the crystalline nature of the surface oxides on these particles. Approximately same view as F2117-2.

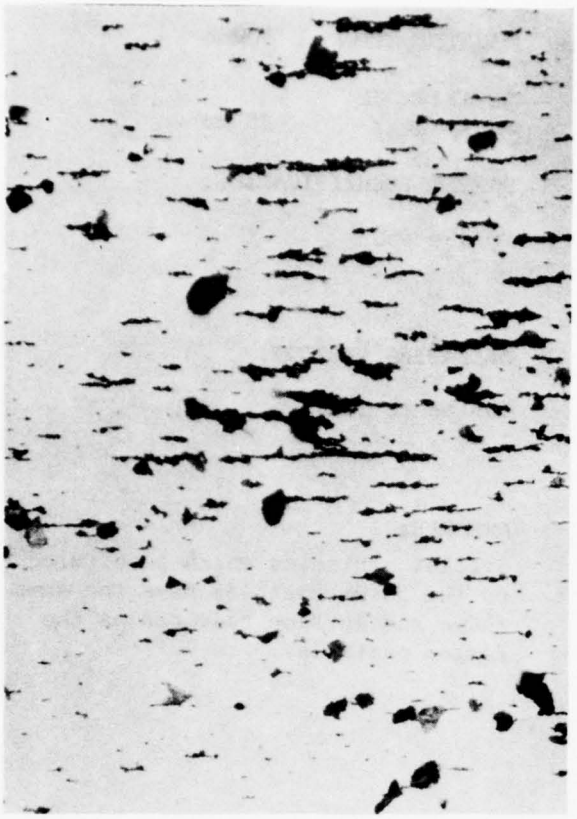


PHOTO NO. F2104-1 DATE 9/22/78

MAGNIFICATION: 100X

LOCATION ON FERROGRAM: Entry

SAMPLE IDENTIFICATION:

Spline #51

OPERATING HISTORY:

Test stopped before failure.

REMARKS:

Overall entry view in bichromatic light. Some particles are sufficiently large, flat, and shiny to reflect red light back thru the optical train.

PHOTO NO. F2104-2 DATE 9/22/78

MAGNIFICATION: 1000X

LOCATION ON FERROGRAM: Entry

SAMPLE IDENTIFICATION:

Spline #51

OPERATING HISTORY:

Test stopped before failure.

REMARKS:

This particle typifies the bright, flat nature of the majority of wear debris deposited on F2117.

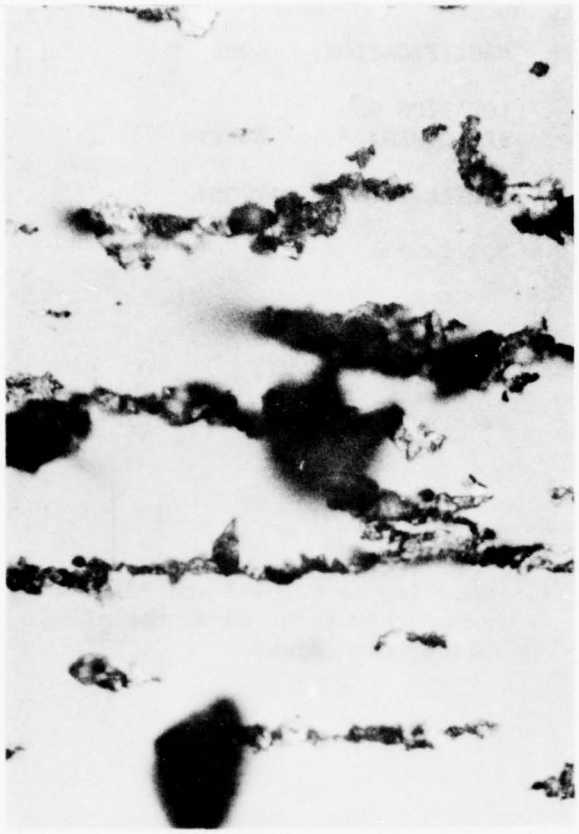


PHOTO NO. F2104-3 DATE 9/22/78

MAGNIFICATION: 400X

LOCATION ON FERROGRAM: Entry

SAMPLE IDENTIFICATION:

Spline #51

OPERATING HISTORY:

Test stopped before failure.

REMARKS:

Most of the wear particles are flat, shiny platelets but several are large chunks.

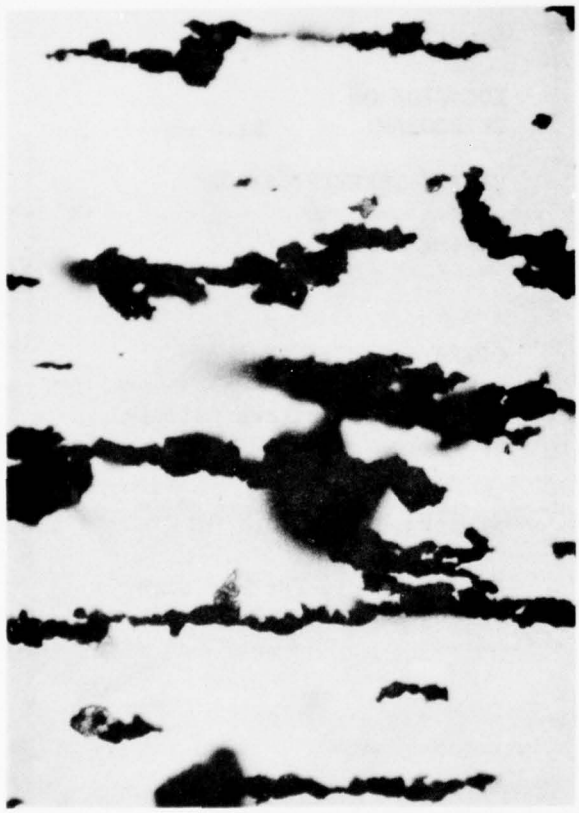


PHOTO NO. F2104-4 DATE 9/22/78

MAGNIFICATION: 400X

LOCATION ON FERROGRAM: Entry

SAMPLE IDENTIFICATION:

Spline #51

OPERATING HISTORY:

Test stopped before failure.

REMARKS:

Same view as F2104-3 above in bichromatic light which demonstrates flatness of particles.

PHOTO NO. F2104-5 DATE 9/22/78

MAGNIFICATION: 400X

LOCATION ON FERROGRAM: Entry

SAMPLE IDENTIFICATION:

Spline #51

OPERATING HISTORY:

Test stopped before failure.

REMARKS:

Same view as F2104-3 and F2104-4 except that focus is on top of spline wear chunk.

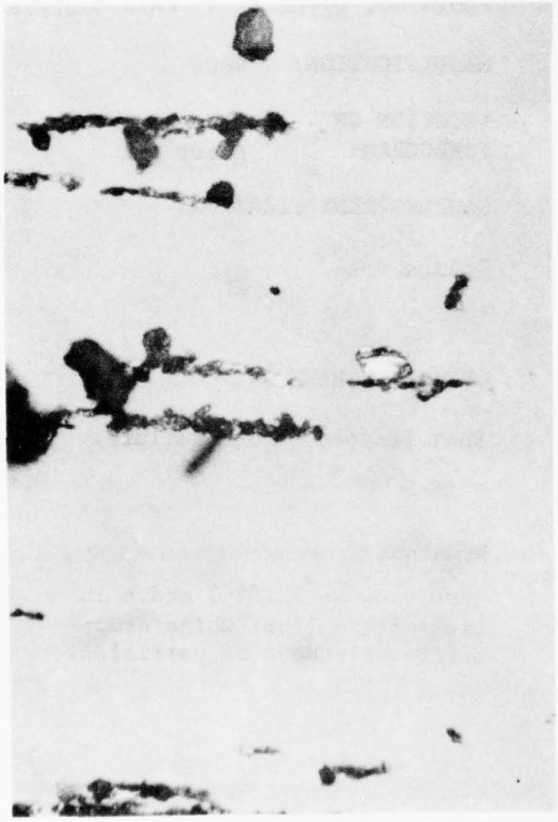


PHOTO NO. F2104-6 DATE 9/22/78

MAGNIFICATION: 400x

LOCATION ON FERROGRAM: 52.0 mm

SAMPLE IDENTIFICATION:

Spline #51

OPERATING HISTORY:

Test stopped before failure.

REMARKS:

Gold particle further along Ferrogram.

In addition to the above included report, various photos with comments were submitted to Nam Suh and colleagues for inclusion in their coated spline report.

In addition to ferrographic analysis of the spline wear debris, the grease used to coat the splines was also analyzed. Various metal particles, oxides, and non-metallic crystalline debris was isolated as well as very fine, needle-shaped, transparent, amorphous particles which are most likely the filler used to raise the viscosity of the oil in order to produce grease. The concentration of contaminants in the grease was thought, by Foxboro Analytical, to be low enough not to adversely affect the life of the splines being tested.

The main conclusion reached from analysis of the failed splines is that the failure mode, once initiated, was similar for all splines, regardless of the coating applied.

7. HYDRAULIC OIL ANALYSIS

From conversations with military and industrial oil analysts, it appears that failures in hydraulic systems are often not predictable by ferrous wear particle monitoring but are due to failure of seals and gaskets which are made from various synthetic organic materials, or from the ingression of other non-metallic contaminants. Application of magnetizing solvents, which contain rare earth salts, developed to precipitate biological materials for medical ferrography, have been successful in precipitating various organic materials from hydraulic oil.

Samples #1 through #4, obtained from an equipment manufacturer, from which ferrograms were prepared using the standard system and using magnetizing solution, demonstrate the potential of this technique. These samples contained progressively more organic material until the equipment failed by the time the fourth sample was taken. This material is identified as fluoroelastomer based on comparison with seal material used in that equipment. Work was not undertaken to microscopically characterize various common hydraulic system materials, which work, it is hoped, could improve hydraulic oil analysis.

Eight photos are presented which show the entry view of the ferrograms prepared both with and without the magnetizing solution for each of the four samples. One cc of sample and 3 cc of either standard solvents or magnetizing solvents were used so that the viscosity of the fluid pumped over the ferrogram would be comparable, if not exactly the same. The photos of the entry views of the first sample (F2409-1 and F2408-1) show that the magnetizing solution deposits more material even before the test run has begun. By the second

sample (F2407-1 and F240601) the magnetizing solution has deposited a significant amount of organic matter which extended down to around the ferrogram 40 mm position. The appearance of the ferrogram made from this sample, when prepared using the magnetizing solution, suggests a failure is under way.

The third and fourth samples contain even more organic debris. The debris was deposited on the ferrogram down to the 25 mm position for the third sample, and to the 6 mm position for the fourth sample. The entry view for the fourth sample prepared using the magnetizing solution, F2402-1, was taken using polarized transmitted light, highlighting several birefringent fibers under the organic debris.

Figures 7-1, 7-2, 7-3, 7-4 show comparisons of ferrogram optical density readings (percent area covered) for the two deposition systems taken at four positions along the ferrograms. Clearly, the magnetic solvent system deposits much more material.

Also included in this report are two more examples of the use of magnetizing solvents. F2608-1 and F2717-1 show entry views of ferrograms prepared from unused oil with and without using the magnetizing procedure, respectively. The distribution of particles on F2717-1 is not uniform because of the disturbance, or damming effect, that the large fiber had on the fluid flow. Photo 2717-2 shows a substantial optically active (i.e., birefringent) deposit at the 50 mm postion when the magnetizing solvent is used on the clean oil.

Photos F2612-1 and F2706-1 compare entry deposits for an engine oil sample prepared with and without magnetizing solvents. The areas circled on F2706-1 are shown in F2706-2 and F2706-3 at higher magnification using the same illumination, namely polarized transmitted light, which causes ordered structures to appear bright against a dark field. The presence of the fibers and the heavy deposits of other non-metallic crystalline debris may indicate a failure in a filter element.

PHOTO NO. F2409-1 DATE 3 June 78

MAGNIFICATION: 100 X

LOCATION ON FERROGRAM: Entry

SAMPLE IDENTIFICATION:
Sample #1
1 cc of sample
standard system

OPERATING HISTORY:

REMARKS:
Oil from equipment before start of test run.

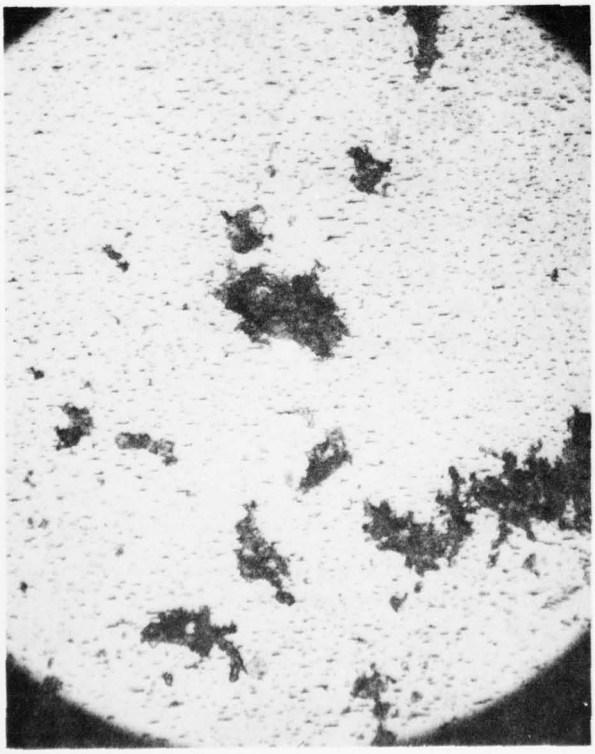


PHOTO NO. F2408-1 DATE 3 June 78

MAGNIFICATION: 100 X

LOCATION ON FERROGRAM: Entry

SAMPLE IDENTIFICATION:
Sample #1
1 cc of sample
magnetic system

OPERATING HISTORY:

REMARKS:
Same sample as above, organic matter present.

PHOTO NO. F2407-1 **DATE** 3 June 78

MAGNIFICATION: 100 X

LOCATION ON FERROGRAM: Entry

SAMPLE IDENTIFICATION:

Sample #2
1 cc of sample
standard system

OPERATING HISTORY:

REMARKS:

Low amount of metallic
and non-metallic debris.

PHOTO NO. F2406-1 **DATE** 3 June 78

MAGNIFICATION: 100 X

LOCATION ON FERROGRAM: Entry

SAMPLE IDENTIFICATION:

Sample #2

magnetic system

OPERATING HISTORY:

REMARKS:

Organic matter on substrate
deposited from entry down
to 50 mm.

PHOTO NO. F2405-1 **DATE** 3 June 78

MAGNIFICATION: 100 X

LOCATION ON FERROGRAM: Entry

SAMPLE IDENTIFICATION:

Sample #3
1 cc of sample
standard system

OPERATING HISTORY:

REMARKS:

Metallic wear increasing, some organic matter at edge of barrier.

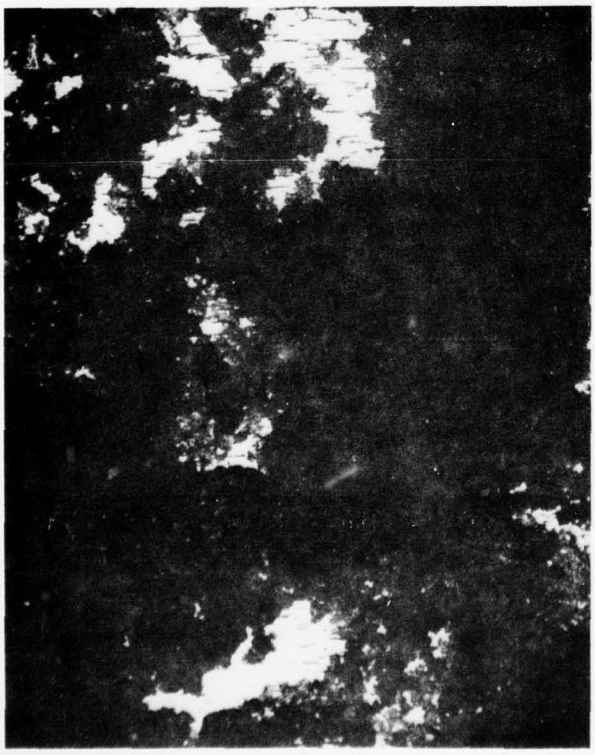


PHOTO NO. F2404 **DATE** 3 June 78

MAGNIFICATION: 100 X

LOCATION ON FERROGRAM: Entry

SAMPLE IDENTIFICATION:

Sample #3
1 cc of sample
magnetic system

OPERATING HISTORY:

REMARKS:

Large amount of organic material obscuring metallic wear, extends down substrate to 25 mm.

PHOTO NO. F2403-1 **DATE** 3 June 78

MAGNIFICATION: 100 X

LOCATION ON FERROGRAM: Entry

SAMPLE IDENTIFICATION:

Sample #4
1 cc of sample
standard system

OPERATING HISTORY:

Equipment failed.

REMARKS:

Organic matter present near edge of barrier.
(Substrate damaged.)

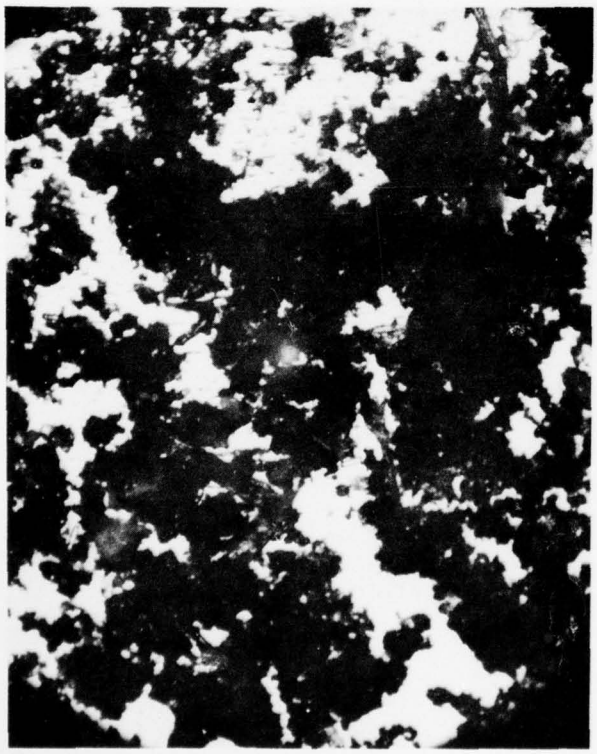


PHOTO NO. F2402-1 **DATE** 3 June 78

MAGNIFICATION: 100 X

LOCATION ON FERROGRAM: Entry

SAMPLE IDENTIFICATION:

Sample #4
1 cc of sample
magnetic system

OPERATING HISTORY:

Equipment failed.

REMARKS:

Large amount of organic matter along substrate down to 6 mm.

FERROGRAPH READINGS
(PERCENT AREA COVERED)

1 CC HYDRAULIC OIL SAMPLE #1

STANDARD FERROGRAPHIC SOLVENT SYSTEM
VS.
MAGNETIC SOLVENT SYSTEM

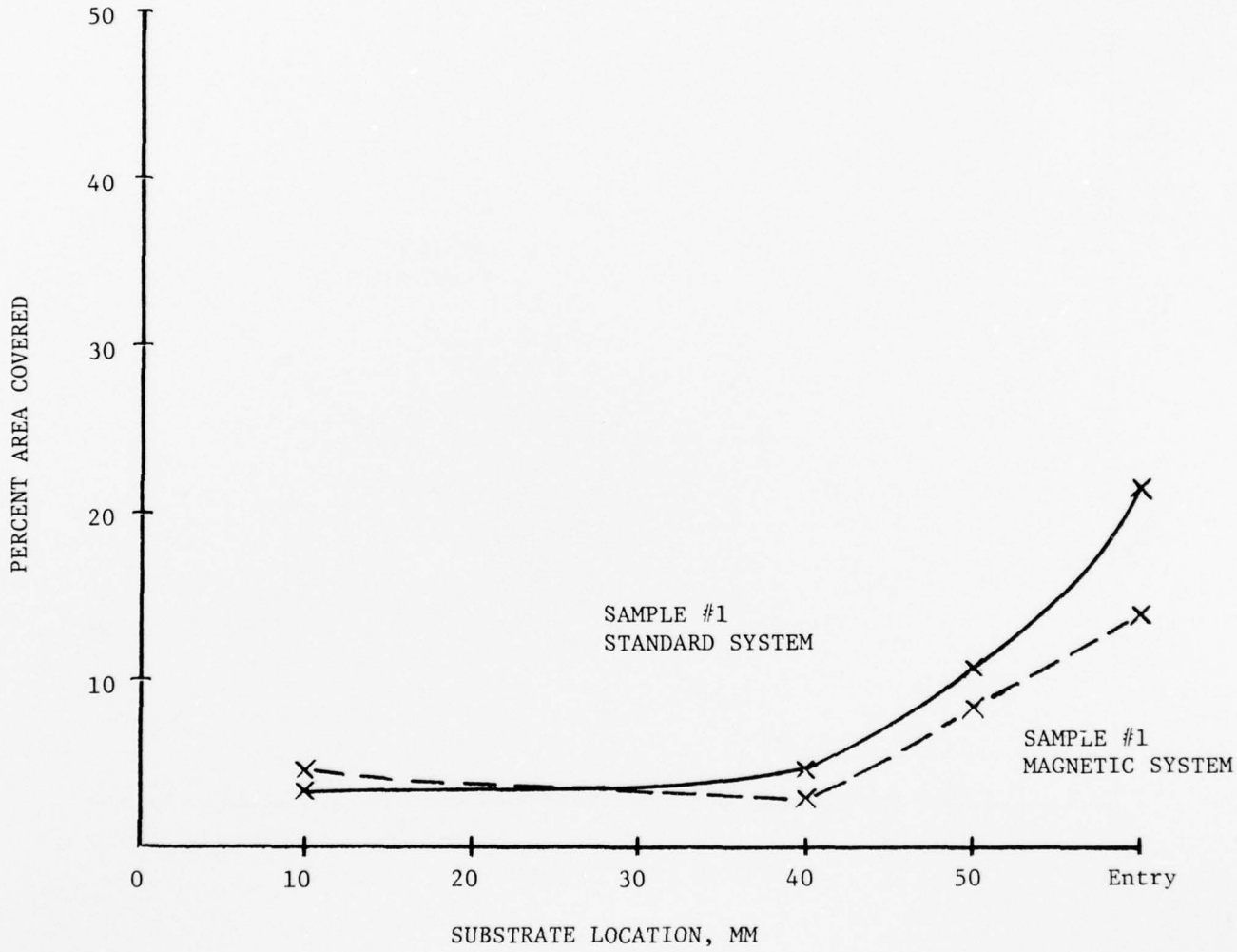


FIGURE 7-1

FERROGRAPH READINGS
(PERCENT AREA COVERED)

1 CC HYDRAULIC OIL SAMPLE #2

STANDARD FERROGRAPHIC SOLVENT SYSTEM
VS.
MAGNETIC SOLVENT SYSTEM

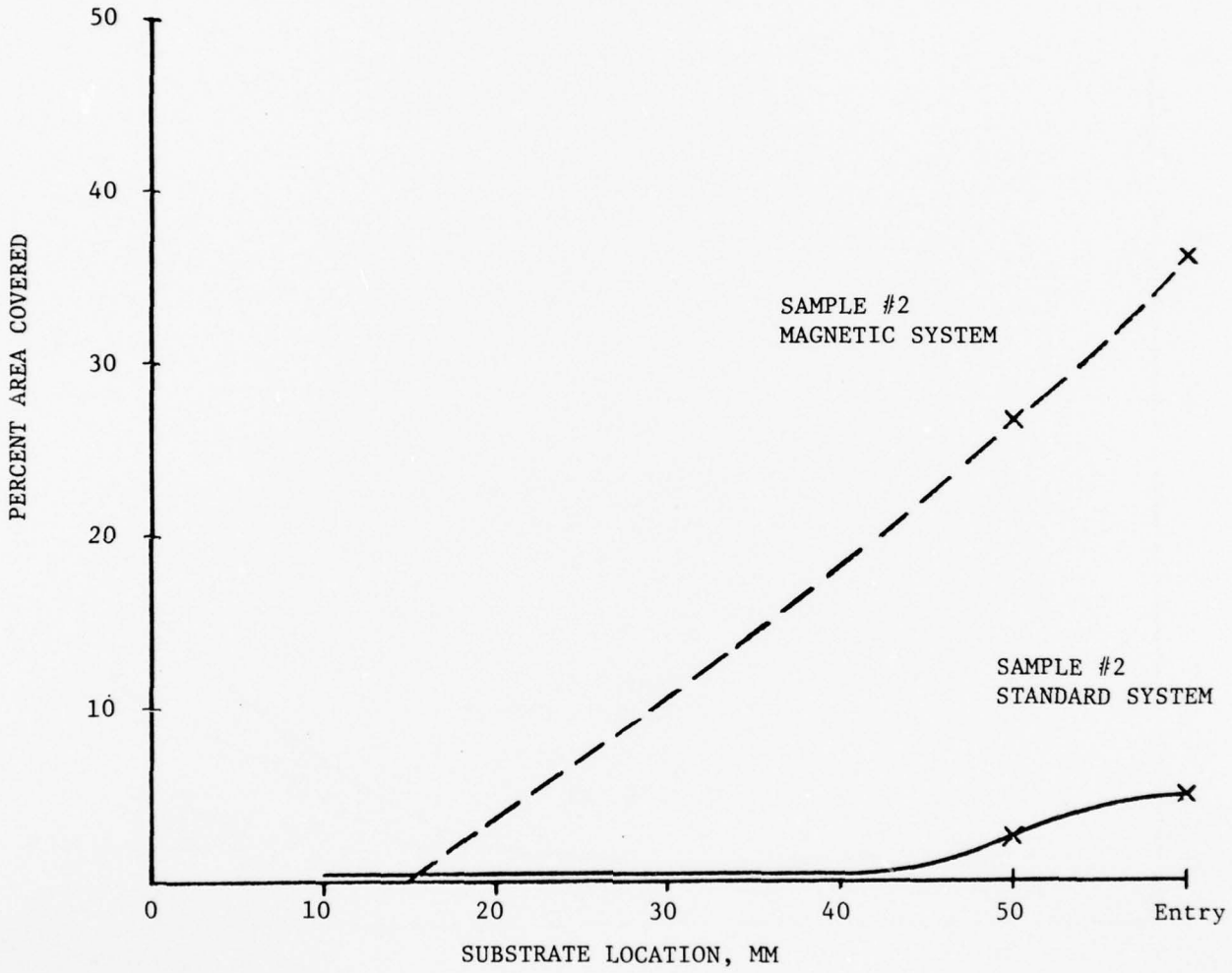


FIGURE 7-2

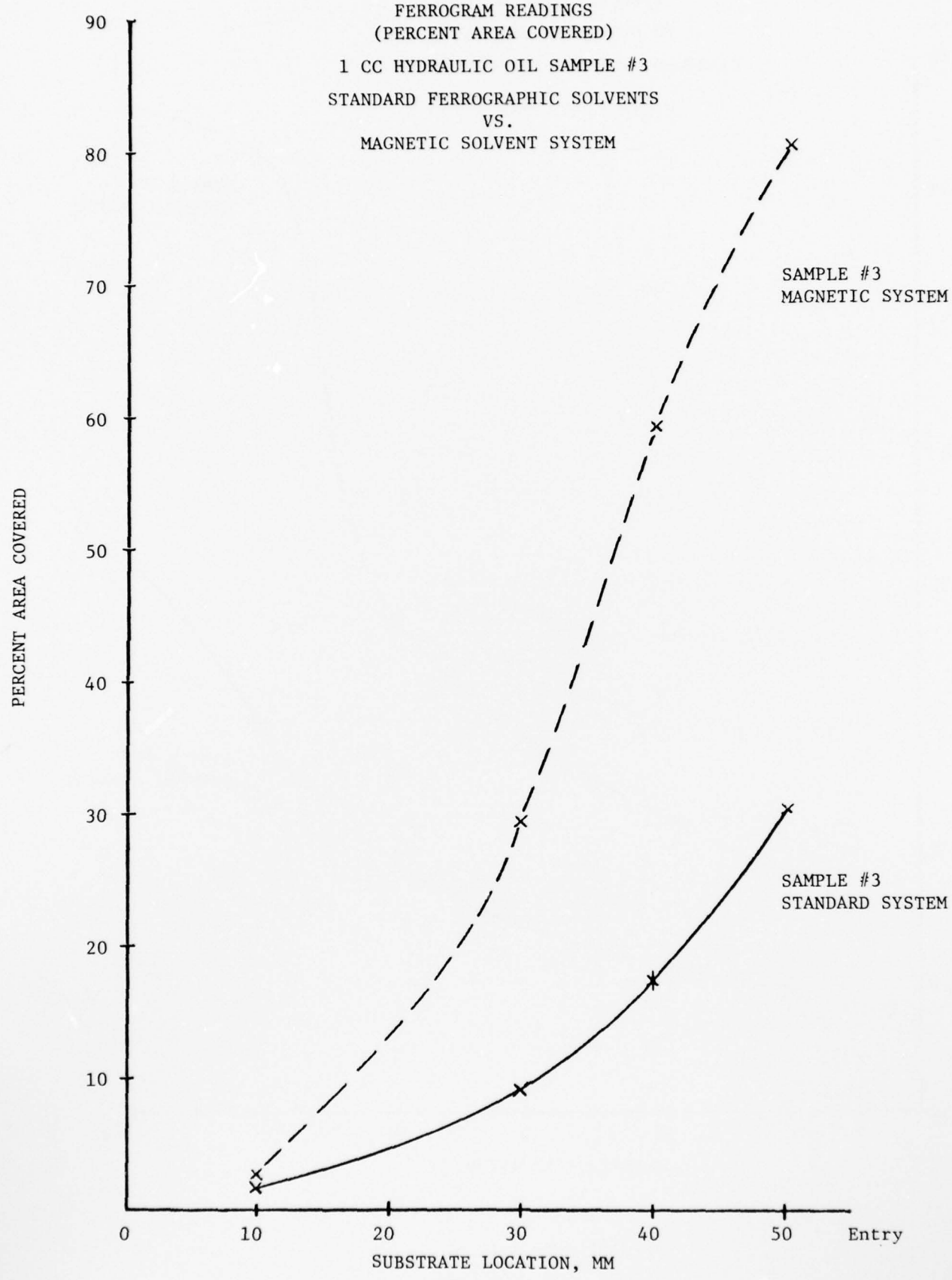

FERROGRAM READINGS
(PERCENT AREA COVERED)
1 CC HYDRAULIC OIL SAMPLE #3
STANDARD FERROGRAPHIC SOLVENTS
VS.
MAGNETIC SOLVENT SYSTEM
SAMPLE #3
MAGNETIC SYSTEM
SAMPLE #3
STANDARD SYSTEM
PERCENT AREA COVERED
90
80
70
60
50
40
30
20
10
0
10
20
30
40
50
Entry
SUBSTRATE LOCATION, MM

FIGURE 7-3

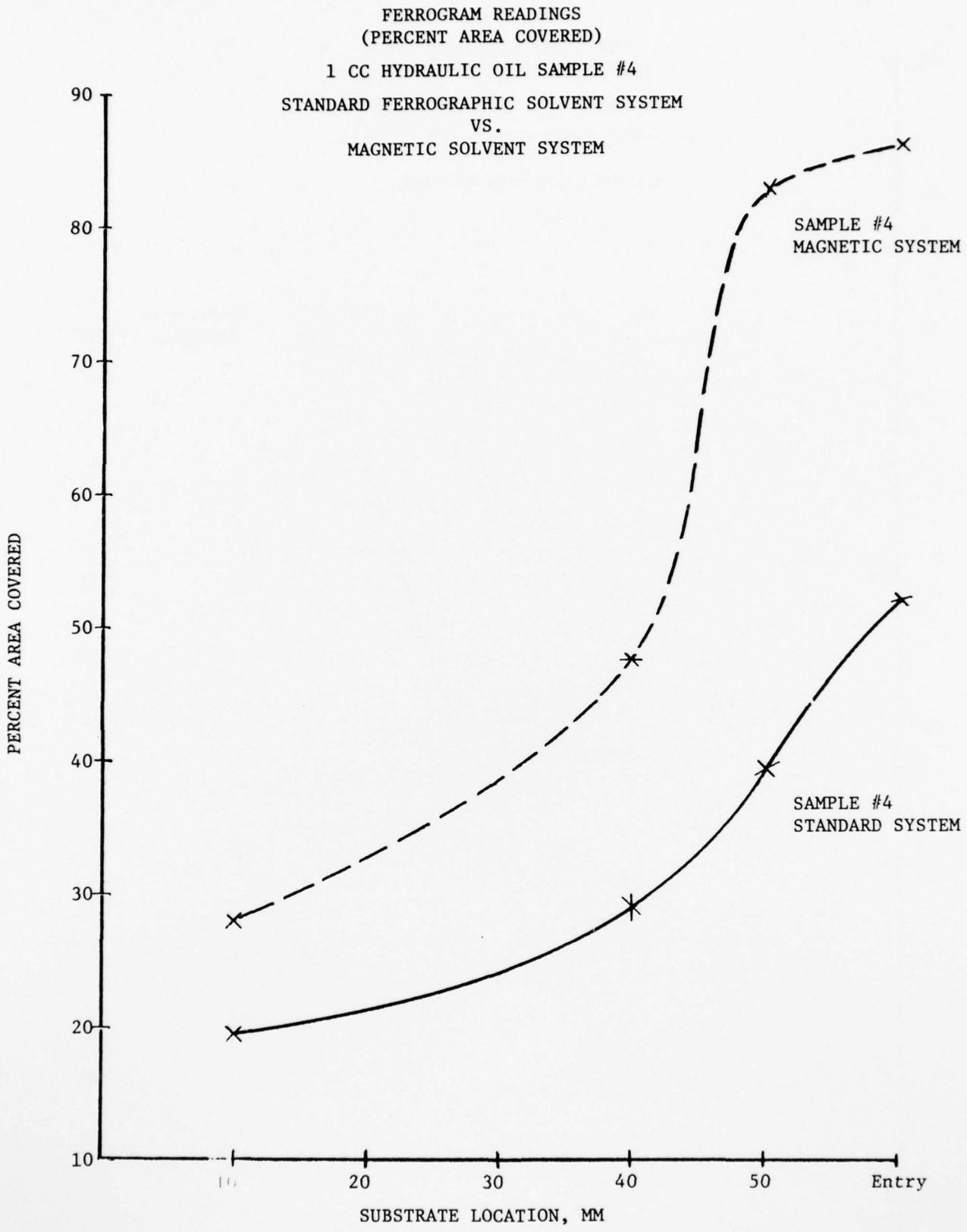

FERROGRAM READINGS
(PERCENT AREA COVERED)
1 CC HYDRAULIC OIL SAMPLE #4
STANDARD FERROGRAPHIC SOLVENT SYSTEM
VS.
MAGNETIC SOLVENT SYSTEM
SAMPLE #4
MAGNETIC SYSTEM
SAMPLE #4
STANDARD SYSTEM
PERCENT AREA COVERED
90
80
70
60
50
40
30
20
10
20
30
40
50
Entry
SUBSTRATE LOCATION, MM

FIGURE 7-4

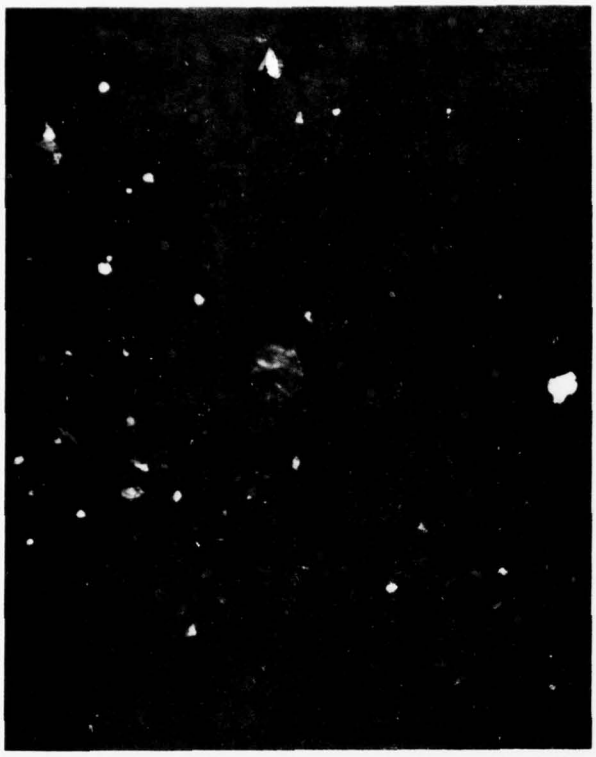


PHOTO NO. F2612-1 DATE

MAGNIFICATION: 100 X

LOCATION ON FERROGRAM: Entry

SAMPLE IDENTIFICATION:

Fluid from an aircraft hydraulic system.

OPERATING HISTORY:

Ferrogram prepared from 1 cc oil and 3 cc of fixer (standard system).

REMARKS:

Photo taken in polarized transmitted light shows low level of non-metallic crystalline contaminants.

PHOTO NO. F2706-1 DATE

MAGNIFICATION: 100 X

LOCATION ON FERROGRAM: Entry

SAMPLE IDENTIFICATION:

Fluid from an aircraft hydraulic system.

OPERATING HISTORY:

Ferrogram prepared from 1 cc oil and 3 cc of magnetizing solvent.

REMARKS:

Photo, taken with same illumination as F2612-1 above, shows deposits of fibers and other birefringent material.

PHOTO NO. F2706-2 DATE

MAGNIFICATION: 400 X

LOCATION ON FERROGRAM: Entry

SAMPLE IDENTIFICATION:

Fluid from an aircraft hydraulic system.

OPERATING HISTORY:

Prepared with magnetizing solvent.

REMARKS:

Higher magnification view of area circled in upper right portion of F2706-1.

PHOTO NO. F2706-3 DATE

MAGNIFICATION: 400 X

LOCATION ON FERROGRAM: Entry

SAMPLE IDENTIFICATION:

Fluid from an aircraft hydraulic system.

OPERATING HISTORY:

Prepared with magnetizing solvent.

REMARKS:

Higher magnification view of fibers circled on F2706-1, again photographed in polarized transmitted light to display birefringence of this material.

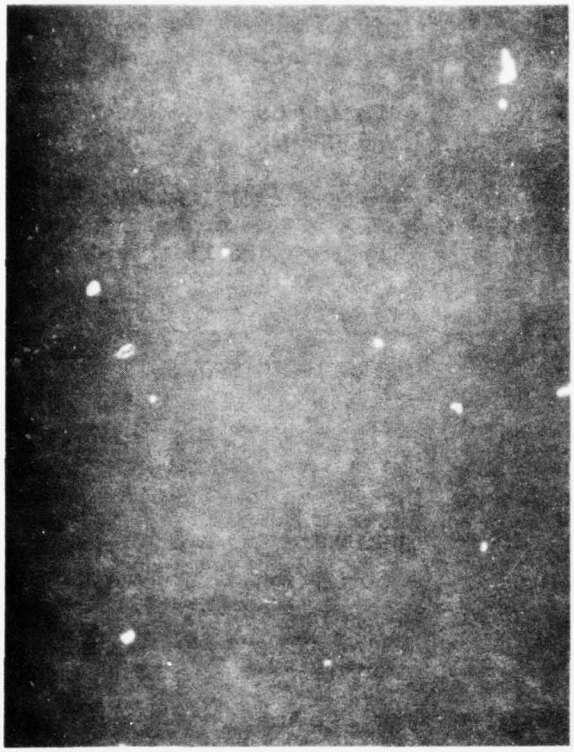


PHOTO NO. F2608-1 DATE

MAGNIFICATION: 100 X

LOCATION ON FERROGRAM: Entry

SAMPLE IDENTIFICATION:

Unused hydraulic fluid

OPERATING HISTORY:

Ferrogram prepared with 1 cc oil and 3 cc of fixer (standard system).

REMARKS:

Ferrogram is quite clean in regard to non-metallic crystalline debris. Photo taken with transmitted polarized light.

PHOTO NO. F2717-1 DATE

MAGNIFICATION: 100 X

LOCATION ON FERROGRAM: Entry

SAMPLE IDENTIFICATION:

Unused hydraulic fluid (same as F2608 above).

OPERATING HISTORY:

Ferrogram prepared with 1 cc oil and 3 cc of magnetizing solvent.

REMARKS:

Great increase in the deposition of non-metallic crystalline debris.

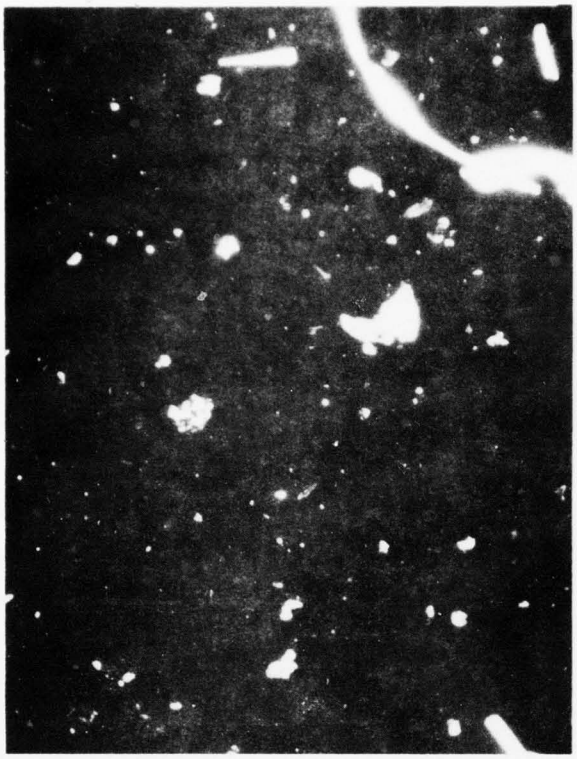


PHOTO NO. F2717-2 DATE

MAGNIFICATION: 100 X

LOCATION ON FERROGRAM: 50 mm

SAMPLE IDENTIFICATION:

Unused hydraulic fluid

OPERATING HISTORY:

REMARKS:

Deposition of non-metallic crystalline material is also enhanced further along ferrogram.

PHOTO NO. DATE

MAGNIFICATION:

LOCATION ON FERROGRAM:

SAMPLE IDENTIFICATION:

OPERATING HISTORY:

REMARKS:

8. MORE QUANTIFIED FERROGRAM ANALYSIS SHEET

A revised ferrogram analysis sheet has been prepared to enable the ferrographer to be more quantitative when analyzing ferrograms. The new sheet, if filled in completely according to instructions, will provide data quantifying the presence of various particle types. Further, the total quantity of particles present is related to the mechanically determined percent area covered ferrogram reading. Advantages of this new reporting method are that small differences between similar particle populations may be more easily detected and that a certain degree of objectivity results from relating total quantity of particles to the ferrogram reading, which presumably is independent of the person making the measurement. A disadvantage is that the method is somewhat more time consuming than that dictated by the previous form.

The old form is presented as Exhibit I and the new form as Exhibit II for purposes of comparison and discussion.

The old form listed the various particle types found in oil lubricated machinery and provided for the analyst to make a judgment regarding their prevalence. Some objectivity was inherent in the old form by virtue of reporting sample dilution, sample volume, and the ferrogram readings. For a given oil sample, the ferrogram readings should be nearly the same for two ferrograms identically prepared. However, the question of whether a certain particle type was present in few, moderate, or heavy amounts was determined subjectively. Further, the old form disregarded position on the ferrograms when describing the types of particles present.

AD-A068 233 FOXBORO ANALYTICAL BURLINGTON MA F/G 14/2
ADVANCES IN WEAR PARTICLE ANALYSIS.(U)
FEB 79 D P ANDERSON, E R BOWEN, J P BOWEN N00014-74-C-0135
UNCLASSIFIED ONR-CR169-007-1F NL

2 OF 2
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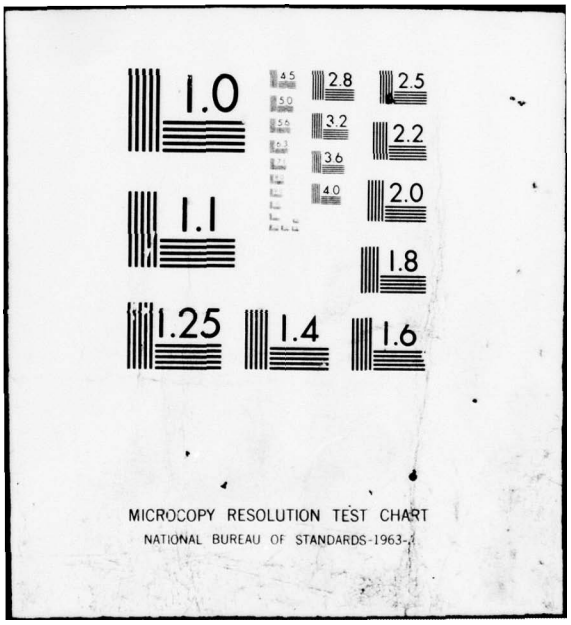
1.0
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5.0
5.6
6.3
MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

The new form attempts to correct these deficiencies by relating the particles present at each ferrogram position to the ferrogram reading obtained at that position. The new form is completed by the following steps:

(1) Upon receipt of a sample for analysis, record such pertinent information as organization, sample number, oil type, etc.

(2) Run a 1 cc sample through the DR ferrograph to determine if dilution (or a larger sample volume) is necessary. A D_L reading of 50 or so indicates that the oil sample has about the right particle concentration to produce a ferrogram that is comfortable to work with. For routine analysis of a well characterized machine, the DR readings may be sufficent to determine that no unusual wear mode has begun. In that case, computation of S_D, the Severity of Wear Index for the DR ferrograph, will result in a value not much different from other values of S_D computed for that machine. If the sample is not routine, or is the first sample obtained for a certain machine, prepare a ferrogram as described below:

(3) Record the dilution factor* necessary to obtain a DR reading of DL = 50. Prepare a ferrogram using 3 cc of diluted sample.

---

* Dilution factor $= \frac{V_1 + V_2}{V_1}$ where

V_1 = Starting volume (or weight) of sample

V_2 = Volume (or weight) of added diluent

(4) Following user instructions, obtain ferrogram readings at the entry and 50 mm position. Ferrogram readings at the 30 mm or 10 mm position may be taken to provide a more thorough analysis, but these positions are not emphasized for ordinary work. Cases such as analysis of hydraulic fluids for non-metallic contamination, or analysis of non-ferrous metal wear, may require attention at positions further along the ferrogram than the 50 mm position.

(5) Compute S_A, the Severity of Wear Index for ferrograms, and compare with other S_A determined for the machine in question. S_A provides a one number synopsis of particle concentration and particle size distribution. See the Wear Particle Atlas[1] for a more complete discussion.

(6) Examine the regions for which ferrogram readings have been obtained to determine what percent area covered is due to each particle type. The contributions from each particle type will total the ferrogram reading for that position except in unusual cases where large transparent bodies, such as friction polymers, overlay metal deposits. The trickiest part of this method is that the ferrogram reading has been obtained using a 10 X objective which encompasses quite a large viewing field, but which ordinarily does not provide sufficient resolution to identify particle types. Therefore, the 100 X objective (and intermediate power objectives if available) must be used to identify particles. A certain amount of switching between objectives will be necessary to gain proper perspective on the prevalence of the various particle types. Various illumination alternatives such as reflected

light, bichromatic light, or polarized light will be helpful sorting out the various particle types.

(7) Spheres are to be counted individually because their contribution to percent area covered is typically negligible.

(8) Copious space is provided for comments which may be directed toward the presence of temper colors, striations on severe wear particles, presence of unusual contaminants, comparison with other ferrograms for the machine under scrutiny, etc. A second sheet may be used to record data after heat treating a ferrogram.

DISCUSSION

Some criticism may be anticipated for the recommendation that lenses must be switched to determine particle type prevalence. The crux of the matter is that to obtain objectivity of the method reference must be made to some mechanically determined measurement. Suggestions have been made that the entire analysis be conducted with an intermediate power objective lens, perhaps 20 X or 40 X. This is impractical because the ability to obtain a repeatable ferrogram reading is seriously compromised by the small field of these lenses and the ability to identify particles is much impaired by the low numerical aperture of these lenses. In fact, it seems an impossible demand to expect one lens to provide statistically valid concentration data as well as provide adequate resolution to identify individual particles.

Some features of the old form have been eliminated because of disuse; namely, the volume of entry, height of entry,

and spectrometer readings. The "considered judgment of wear situation" has been eliminated because often judgment is imprudent for want of trend data.

Six automotive samples from a fleet test conducted by the National Bureau of Standards in Iowa state in which three samples were supposed to be re-refined oil and three samples were supposed to be virgin stock have been analyzed using the new sheet. The samples were not identified to the analyst. The subsequent ferrographic analysis revealed only small differences in concentration and particle type among these samples. Nevertheless, the analyst ranked the samples best to worst in the order 1004, 1001, 1005, 1002, 1003, 1006 based on the Severity of Wear Index, the presence of severe wear particles, oxides, etc. Details of the analysis are summarized on Tables 8-I and 8-II. It turned out that there were only three samples; they had been submitted in duplicate. Samples 1002 and 1004 were the same (a re-refined oil from the same car), samples 1003 and 1006 (re-refined) were the same, and samples 1001 and 1005 were the same (virgin oil). Looking at the ranking, 1001 and 1005 were grouped contiguously, as were 1003 and 1006, but 1002 and 1004 were not. The results were encouraging to the analyst given the great similarity between samples.

Unfortunately, this method took significantly longer to apply per ferrogram than did the old, more subjective method. A great deal of comparison between ferrograms, requiring that each ferrogram be put on the microscope stage many times, was necessary to arrive at percent area covered figures for each particle type so that the data was internally consistent. For example, if for one ferrogram, 2.0% is assigned to the area covered by dark-metallo oxides, the

next ferrogram, which appears to have twice the concentration of dark-metallo oxides, must be assigned 4.0% area covered. On the other hand, the sum of all the percent area covered figures for the various particle types must equal the mechanically determined reading. Considerable juggling of the figures, as the ferrograms are compared, is needed to assure that each particle type is ranked properly on each ferrogram and that the sum of the contribution from each particle type equals the total.

Foxboro Analytical suggests that the more quantitative method, which the auto fleet test analysis indicates is fairly effective, be used only where small differences between samples need be detected. Some research applications may require this accuracy. However, for routine failure prevention, the extra effort does not seem justified since the concentration and morphological changes that occur before failure are readily detectable.

(1) Bowen, E.R. and Westcott, V.C., "Wear Particle Atlas", Foxboro/Trans-Sonics, Inc., Burlington, MA 01803. Prepared for Naval Air Engineering Center, Lakehurst, N.J., 98733, July 1976.

FERROGRAM ANALYSIS REPORT

Ferrogram No.:_____ Date:_____

Organization:_____ Sample No.:_____

Equip. Type:_____ Serial No.:_____ Operating Time:_____

Sample Date:_____ Oil Type_____ Time on Oil:_____

Replenishment Data:_____

Volume of Sample passed along Ferrogram _____ cc Entry 54mm 50mm 10mm

Ferrogram Reading (% area covered) ____ ____ ____ ____

Volume of Entry _____ um^3 Height of Entry Deposit _____ um

Types of Particles	None	Few	Moderate	Heavy
Normal Rubbing Wear				
Fatigue Chunks (Typical gear surface fatigue)				
Spheres (fatigue cracks in rolling bearings)				
Laminar Particles (gears or rolling bearings)				
Severe Wear Particles				
Cutting Wear Particles (high unit pressure)				
Corrosive Wear Particles				
Oxides Particles (includes rust)				
Dark Metallo-oxide Particles (typical hard steels)				
Non-ferrous Metallic				
Non-metallic, Crystalline				
Non-metallic, Amorphous (i.e. friction polymer)				

Considered Judgement of Wear Situation

	Very Low		Normal		Caution		Very High (Red Alert)

Emission Spectrometer PPM

Al	Fe	Cr	Ag	Cu	Sn	Mg	Ti	Ni	Si

Comments: EXHIBIT I

FERROGRAM ANALYSIS SHEET

Ferrogram No._____ Date_____ DR Reading D_L_____ D_S_____

Organization_____ $S_D = n^2 \left(D_L^2 - D_S^2 \right)$ = _____

Sample No._____ Equipment Type_____

Serial No._____ Operating Time_____ Oil Type_____

Dilution Factor (n) = _____ Volume of diluted sample passed along Ferrogram _____ cc.

Ferrogram Reading (% Area Covered) @100 X magnification	Entry, A_L	50 mm, A_S	30 mm	10 mm
SEVERITY OF WEAR INDEX →	$S_A = n^2 (A_L^2 - A_S^2)$ =			
Types of Particles, estimated % of area covered by each particle type @ each position.	Entry	50 mm	30 mm	10 mm
Normal rubbing wear particles				
Severe wear particles				
Cutting wear particles				
Fatigue chunks				
Laminar particles				
Dark metallo-oxide particles				
Oxide particles				
Non-ferrous metallic particles				
Corrosive wear particles				
Non-metallic, crystalline				
Non-metallic, amorphous				
Friction polymer				
Other, specify_____				
% TOTAL				
Spheres, by count at 1000 X				

Comments:_____

EXHIBIT II

	ENTRY DATA					
FERROGRAM NO.	2154	2155	2156	2157	2158	2159
SAMPLE	1001	1002	1003	1004	1005	1006
Ferrogram Reading	8.5	10.1	10.9	10.7	11.2	12.6
Severity of Wear Index	36	35	47	54	101	74
Normal Rubbing Wear	4.3	8.0	5.9	8.3	5.4	7.1
Severe Wear	0.1	0.5	0.7		0.2	1.5
Cutting Wear						
Fatigue Chunks						
Laminar Particles						
Dark-Metallo Oxide	2.5	1.0	3.5	2.0	2.0	2.0
Red Oxide	0.1	0.1	0.2	0.1	0.4	0.8
Non-Ferrous Metal						
Corrosive Wear			0.1	0.1	0.1	0.2
Non-Metallic Crystalline	1.5	0.5	0.5	0.2	3.0	1.0
Non-Metallic Amorphous						
Friction Polymer					0.1	
TOTAL	8.5	10.1	10.9	10.7	11.2	12.6
Spheres, by count			4			6
Best-to-Worst Ranking	1004	1001	1005	1002	1003	1006

FIGURE 8-1

	50 mm POSITION DATA					
FERROGRAM NO.	2154	2155	2156	2157	2158	2159
SAMPLE	1001	1002	1003	1004	1005	1006
Ferrogram Readings	6.0	8.2	8.5	7.8	4.9	9.2
Severity of Wear Index	36	35	47	54	101	74
Normal Rubbing Wear	3.0	6.3	4.2	5.2	2.8	6.3
Severe Wear						
Cutting Wear						
Fatigue Chunks						
Laminar Particles						
Dark-Metallo Oxide	2.0	1.0	3.0	2.0	1.5	2.0
Red Oxide	0.5	0.2	0.5		0.2	0.2
Non-Ferrous Metal			0.2			
Corrosive Wear	0.5	0.2	0.5	0.4	0.2	0.2
Non-Metallic Crystalline		0.5	0.1	0.2	0.2	0.5
Non-Metallic Amorphous						
Friction Polymer						
TOTAL	6.0	8.2	8.5	7.8	4.9	9.2
Spheres, by count						

FIGURE 8-2

9. TTCP

Ferrographic analysis was performed on four sets of samples, each set from a different laboratory, for The Technical Cooperation Program (TTCP). These samples were also analyzed by the various participating laboratories and results were compared by the Working Party on the Characterization of Wear in Oil Lubricated Systems. The anlysis report prepared by Foxboro Analytical follows.

THE TECHNICAL COOPERATION PROGRAM (TTCP)

CHARACTERIZATION OF WEAR IN OIL LUBRICATED SAMPLES

AUGUST 1977

THE TECHNICAL COOPERATION PROGRAM (TTCP)

Characterization of Wear in Oil Lubricated Samples

TABLE OF CONTENTS

SECTION 1 - Ferrographic Analysis of Ten (10) Oil Samples, ADMIRALTY MATERIALS LABORATORY, Holton Heath, Poole, Dorset, U. K. -
Helicopter Test Rig Gear Box

SECTION 2 - Ferrographic Analysis of Four (4) Oil Samples from AUSTRALIAN RESEARCH LABORATORIES -
Test rig

SECTION 3 - Ferrographic Analysis of Four (4) Oil Samples from DEPARTMENT OF THE NAVY, OFFICE OF NAVAL RESEARCH, WASHINGTON, D.C.
Helicopter Transmission (non-failure)

SECTION 4 - Ferrographic Analysis of Three (3) Separate Oil Samples from NAVAL AIR ENGINEERING CENTER, LAKEHURST, NEW JERSEY

! August 1977

FOXBORO

FERROGRAPHIC ANALYSIS

SECTION ONE

ADMIRALTY MATERIALS LABORATORY
HOLTON HEATH, POOLE, DORSET, U. K.

Foxboro/Trans-Sonics, Inc. 8 July 77

FERROGRAPHIC ANALYSIS REPORT

RE: TTCP Program - oil samples from Scout/WASP
WAB/Dev/104, Helicopter Gear Box Test Rig.

Ferrogram Readings (% area covered) of this series of oil samples show a sharp increase in the density of the deposit and the Severity of Wear Index (I_S) from the first sample (0.33 hours on oil) up to sample #3 (5 hours on oil), then a decline thereafter. Refer to Table I and Figure I. The exception to this Severity of Wear Index drop was in sample number 10 (40 hrs. on oil) but subsequent microscopic examination of the Ferrogram of the particular sample show it is not in a severe wear category. Oil sample #4 (12 hours on oil) was broken in transit so we can only say that the peak of the Severity of Wear Index curve is somewhere between five and fifteen hours on the oil.

Microscopic examination of the Ferrograms show wear conditions paralleling the Ferrogram Readings. Samples #1, #2, and #3 show an increasing amount of both normal rubbing wear and severe wear particles. The size of the severe wear particles is largest in sample #3 (see photos F1601-1, F1602-1, and F1603-1, -2).

All of the Ferrograms of the first three smaples show a blue oxide temper color on some of the wear particles which is evidence of conditions of high temperature and pressure. Ferrograms of samples #5 - 11 show a decline in the amount and size of the wear particles and this corresponds to the Ferrogram Readings A_L curve in Figure I. Samples #5 and #6 do show minor evidence of the blue oxide temper color but this is not found in subsequent samples.

In summary, Ferrographic Analysis of the series of oil samples shows a standard wear situation of initially high wear particle generation in the startup or break-in phase then a normal operating mode thereafter.

FOXBORO

TABLE I

Oil Sample No.	Hours	Ferrogram No.	Readings % Area A_L Entry	A_S 50 mm	A_S 10 mm	Severity of Wear Index $I_S = A_L^2 - A_S^2$
1	0.33	F1601	10.2	5.8	1.0	74
2	1	F1602	24.4	16.3	4.6	329
3	5	F1603	31.9	24.2	5.7	432
4	(sample missing)					
5	15	F1605	18.7	10.8	1.8	233
6	20	F1606	9.2	8.3	2.2	16
7	25	F1607	10.9	7.1	1.0	69
8	30	F1608	15.2	11.5	2.0	99
9	35	F1609	9.9	7.0	2.1	49
10	40	F1610	19.4	6.8	1.0	330
11	45	F1612	10.0	4.8	0.9	77

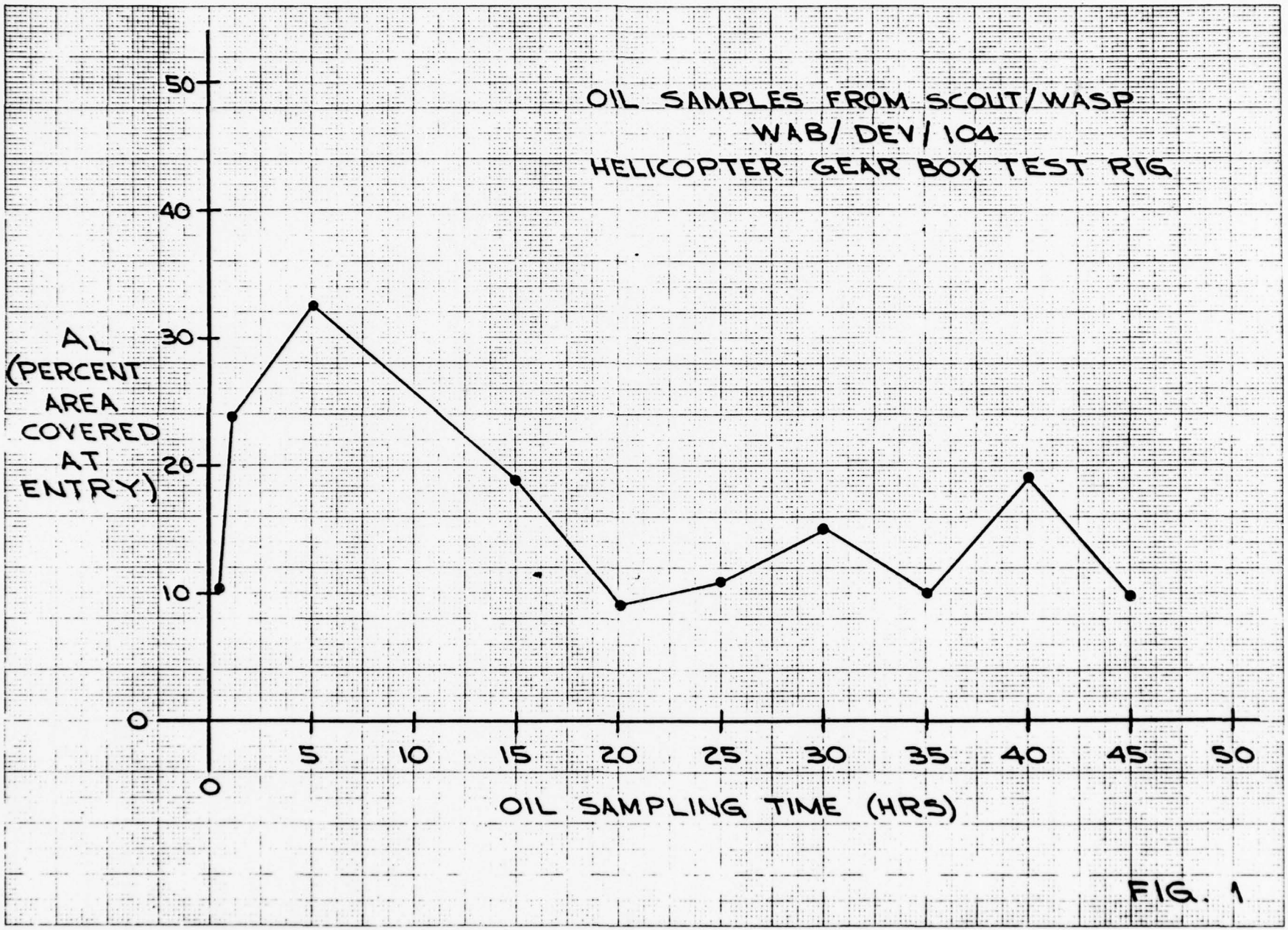
OIL SAMPLES FROM SCOUT/WASP
WAB/DEV/104
HELICOPTER GEAR BOX TEST RIG
AL (PERCENT AREA COVERED AT ENTRY)
50
40
30
20
10
0
0
5
10
15
20
25
30
35
40
45
50
OIL SAMPLING TIME (HRS)

FIG. 1

FERROGRAM ANALYSIS REPORT

Ferrogram No.: F1601 Date: 7/5/77

Organization: TTCP Sample No.: #1

Equip. Type: Helicopter gear box Serial No.: Operating Time: 0.33 hrs.

Sample Date: Oil Type OEP 215 mineral Time on Oil:

Replenishment Data: 10:1 dilution

Volume of Sample passed along Ferrogram 2.0 cc

	Entry	54mm	50mm	10mm
Ferrogram Reading (% area covered)	10.2		5.8	1.0

Volume of Entry _____ um^3 Height of Entry Deposit _____ um

Types of Particles	None	Few	Moderate	Heavy
Normal Rubbing Wear			X	
Fatigue Chunks (Typical gear surface fatigue)	X			
Spheres (fatigue cracks in rolling bearings)	X			
Laminar Particles (gears or rolling bearings)	X			
Severe Wear Particles		X(1)		
Cutting Wear Particles (high unit pressure)	X			
Corrosive Wear Particles	X			
Oxides Particles (includes rust)		X		
Dark Metallo-oxide Particles (typical hard steels)		X		
Non-ferrous Metallic				
Non-metallic, Crystalline		X		
Non-metallic, Amorphous (i.e. friction polymer)	X			

Considered Judgement of Wear Situation

	Very Low		Normal		Caution		Very High (Red Alert)

Emission Spectrometer PPM

Al	Fe	Cr	Ag	Cu	Sn	Mg	Ti	Ni	Si

Comments: (1) Distinct blue oxide temper color on some particles

FERROGRAM ANALYSIS REPORT

Ferrogram No.: F1602 Date: 7/5/77

Organization: TTCP Sample No.: #2

Equip. Type: Helicopter gear box Serial No.: Operating Time: 1.0 hrs.

Sample Date: Oil Type OEP 215 mineral Time on Oil:

Replenishment Data: 10:1 dilution

Volume of Sample passed along Ferrogram 2.0 cc

	Entry	54mm	50mm	10mm
Ferrogram Reading (% area covered)	24.4		16.3	4.6

Volume of Entry _____ um^3 Height of Entry Deposit _____ um

Types of Particles	None	Few	Moderate	Heavy
Normal Rubbing Wear			X	
Fatigue Chunks (Typical gear surface fatigue)	X			
Spheres (fatigue cracks in rolling bearings)	X			
Laminar Particles (gears or rolling bearings)	X			
Severe Wear Particles			X(1)	
Cutting Wear Particles (high unit pressure)	X			
Corrosive Wear Particles	X			
Oxides Particles (includes rust)	X			
Dark Metallo-oxide Particles (typical hard steels)		X		
Non-ferrous Metallic	X			
Non-metallic, Crystalline		X		
Non-metallic, Amorphous (i.e. friction polymer)	X			

Considered Judgement of Wear Situation

	Very Low		Normal		Caution		Very High (Red Alert)

Emission Spectrometer PPM

Al	Fe	Cr	Ag	Cu	Sn	Mg	Ti	Ni	Si

Comments: (1) Distinct blue oxide temper color present

FERROGRAM ANALYSIS REPORT

Ferrogram No.: F1603 Date: 7/5/77

Organization: TTCP Sample No.: #3

Equip. Type: Helicopter gear box Serial No.: Operating Time: 5 hrs.

Sample Date: Oil Type OEP 215 mineral Time on Oil:

Replenishment Data: 10:1 dilution

Volume of Sample passed along Ferrogram 2.0 cc

	Entry	54mm	50mm	10mm
Ferrogram Reading (% area covered)	31.9		24.2	5.7

Volume of Entry _____ um^3 Height of Entry Deposit _____ um

Types of Particles	None	Few	Moderate	Heavy
Normal Rubbing Wear				X
Fatigue Chunks (Typical gear surface fatigue)	X			
Spheres (fatigue cracks in rolling bearings)	X			
Laminar Particles (gears or rolling bearings)	X			
Severe Wear Particles				X(1)
Cutting Wear Particles (high unit pressure)		X		
Corrosive Wear Particles	X			
Oxides Particles (includes rust)		X		
Dark Metallo-oxide Particles (typical hard steels)		X		
Non-ferrous Metallic	X			
Non-metallic, Crystalline		X		
Non-metallic, Amorphous (i.e. friction polymer)	X			

Considered Judgement of Wear Situation

	Very Low		Normal		Caution		Very High (Red Alert)

Emission Spectrometer PPM

Al	Fe	Cr	Ag	Cu	Sn	Mg	Ti	Ni	Si

Comments: (1) Distinct blue oxide temper color

FERROGRAM ANALYSIS REPORT

Ferrogram No.: F1605 Date: 7/5/77

Organization: TTCP Sample No.: #5

Equip. Type: Helicopter gear box Serial No.: Operating Time: 15 hrs.

Sample Date: Oil Type OEP 215 mineral Time on Oil:

Replenishment Data: 10:1 dilution

Volume of Sample passed along Ferrogram 2.0 cc

	Entry	54mm	50mm	10mm
Ferrogram Reading (% area covered)	18.7		10.8	1.8

Volume of Entry _____ um^3 Height of Entry Deposit _____ um

Types of Particles	None	Few	Moderate	Heavy
Normal Rubbing Wear			X	
Fatigue Chunks (Typical gear surface fatigue)	X			
Spheres (fatigue cracks in rolling bearings)	X			
Laminar Particles (gears or rolling bearings)	X			
Severe Wear Particles		X		
Cutting Wear Particles (high unit pressure)	X			
Corrosive Wear Particles	X			
Oxides Particles (includes rust)		X		
Dark Metallo-oxide Particles (typical hard steels)		X		
Non-ferrous Metallic	X			
Non-metallic, Crystalline		X		
Non-metallic, Amorphous (i.e. friction polymer)	X			

Considered Judgement of Wear Situation

	Very Low		Normal		Caution		Very High (Red Alert)

Emission Spectrometer PPM

Al	Fe	Cr	Ag	Cu	Sn	Mg	Ti	Ni	Si

Comments: Traces of blue oxide temper color

FERROGRAM ANALYSIS REPORT

Ferrogram No.: F1606 Date: 7/5/77

Organization: TTCP Helicopter Sample No.: #6

Equip. Type: gear box Serial No.: Operating Time: 20 hrs.

Sample Date: Oil Type OEP 215 mineral Time on Oil:

Replenishment Data: 10:1 dilution

Volume of Sample passed along Ferrogram 2.0 cc

	Entry	54mm	50mm	10mm
Ferrogram Reading (% area covered)	9.2		8.3	2.2

Volume of Entry _____ um^3 Height of Entry Deposit _____ um

Types of Particles	None	Few	Moderate	Heavy
Normal Rubbing Wear		X		
Fatigue Chunks (Typical gear surface fatigue)	X			
Spheres (fatigue cracks in rolling bearings)	X			
Laminar Particles (gears or rolling bearings)	X			
Severe Wear Particles		X		
Cutting Wear Particles (high unit pressure)	X			
Corrosive Wear Particles	X			
Oxides Particles (includes rust)		X		
Dark Metallo-oxide Particles (typical hard steels)		X		
Non-ferrous Metallic	X			
Non-metallic, Crystalline		X		
Non-metallic, Amorphous (i.e. friction polymer)	X			

Considered Judgement of Wear Situation

	Very Low		Normal		Caution		Very High (Red Alert)

Emission Spectrometer PPM	Al	Fe	Cr	Ag	Cu	Sn	Mg	Ti	Ni	Si

Comments: Traces of blue oxide temper color

FERROGRAM ANALYSIS REPORT

Ferrogram No.: F1607 Date: 7/5/77

Organization: TTCP Sample No.: #7

Equip. Type: Helicopter gear box Serial No.: Operating Time: 25 hrs.

Sample Date: Oil Type OEP 215 mineral Time on Oil:

Replenishment Data: 10:1 dilution

Volume of Sample passed along Ferrogram 2.0 cc

	Entry	54mm	50mm	10mm
Ferrogram Reading (% area covered)	10.9		7.1	1.0

Volume of Entry _____ um^3 Height of Entry Deposit _____ um

Types of Particles	None	Few	Moderate	Heavy
Normal Rubbing Wear		X		
Fatigue Chunks (Typical gear surface fatigue)	X			
Spheres (fatigue cracks in rolling bearings)	X			
Laminar Particles (gears or rolling bearings)	X			
Severe Wear Particles		X		
Cutting Wear Particles (high unit pressure)	X			
Corrosive Wear Particles	X			
Oxides Particles (includes rust)		X		
Dark Metallo-oxide Particles (typical hard steels)		X		
Non-ferrous Metallic	X			
Non-metallic, Crystalline		X		
Non-metallic, Amorphous (i.e. friction polymer)	X			

Considered Judgement of Wear Situation

	Very Low		Normal		Caution		Very High (Red Alert)

Emission Spectrometer PPM

Al	Fe	Cr	Ag	Cu	Sn	Mg	Ti	Ni	Si

Comments: _____

FERROGRAM ANALYSIS REPORT

Ferrogram No.: F1608 Date: 7/5/77

Organization: TTCP Sample No.: #8

Equip. Type: Helicopter gear box Serial No.: Operating Time: 30 hrs.

Sample Date: Oil Type OEP 215 mineral Time on Oil:

Replenishment Data: 10:1 dilution

Volume of Sample passed along Ferrogram 2.0 cc

	Entry	54mm	50mm	10mm
Ferrogram Reading (% area covered)	15.2		11.5	2.0

Volume of Entry _____ um^3 Height of Entry Deposit _____ um

Types of Particles	None	Few	Moderate	Heavy
Normal Rubbing Wear		X		
Fatigue Chunks (Typical gear surface fatigue)	X			
Spheres (fatigue cracks in rolling bearings)	X			
Laminar Particles (gears or rolling bearings)	X			
Severe Wear Particles		X		
Cutting Wear Particles (high unit pressure)	X			
Corrosive Wear Particles	X			
Oxides Particles (includes rust)		X		
Dark Metallo-oxide Particles (typical hard steels)		X		
Non-ferrous Metallic	X			
Non-metallic, Crystalline		X		
Non-metallic, Amorphous (i.e. friction polymer)	X			

Considered Judgement of Wear Situation

	Very Low		Normal		Caution		Very High (Red Alert)

Emission Spectrometer PPM

Al	Fe	Cr	Ag	Cu	Sn	Mg	Ti	Ni	Si

Comments: _____

FERROGRAM ANALYSIS REPORT

Ferrogram No.: F1609 Date: 7/5/77

Organization: TTCP Sample No.: #9

Equip. Type: Helicopter gear box Serial No.: Operating Time: 35 hrs.

Sample Date: Oil Type OEP 215 mineral Time on Oil:

Replenishment Data: 10:1 dilution

Volume of Sample passed along Ferrogram 2.0 cc

	Entry	54mm	50mm	10mm
Ferrogram Reading (% area covered)	9.9		7.0	2.1

Volume of Entry _____ um^3 Height of Entry Deposit _____ um

Types of Particles	None	Few	Moderate	Heavy
Normal Rubbing Wear		X		
Fatigue Chunks (Typical gear surface fatigue)	X			
Spheres (fatigue cracks in rolling bearings)	X			
Laminar Particles (gears or rolling bearings)	X			
Severe Wear Particles		X		
Cutting Wear Particles (high unit pressure)	X			
Corrosive Wear Particles	X			
Oxides Particles (includes rust)		X		
Dark Metallo-oxide Particles (typical hard steels)		X		
Non-ferrous Metallic	X			
Non-metallic, Crystalline		X		
Non-metallic, Amorphous (i.e. friction polymer)	X			

Considered Judgement of Wear Situation

	Very Low		Normal		Caution		Very High (Red Alert)

Emission Spectrometer PPM

Al	Fe	Cr	Ag	Cu	Sn	Mg	Ti	Ni	Si

Comments: _____

FERROGRAM ANALYSIS REPORT

Ferrogram No.: F1610 Date: 7/5/77

Organization: TTCP Sample No.: #10

Equip. Type: Helicopter gear box Serial No.: Operating Time: 40 hrs.

Sample Date: Oil Type OEP 215 mineral Time on Oil:

Replenishment Data: 10:1 dilution

Volume of Sample passed along Ferrogram 2.0 cc

	Entry	54mm	50mm	10mm
Ferrogram Reading (% area covered)	19.4		6.8	1.0

Volume of Entry _____ um^3 Height of Entry Deposit _____ um

Types of Particles	None	Few	Moderate	Heavy
Normal Rubbing Wear		X		
Fatigue Chunks (Typical gear surface fatigue)	X			
Spheres (fatigue cracks in rolling bearings)	X			
Laminar Particles (gears or rolling bearings)	X			
Severe Wear Particles		X		
Cutting Wear Particles (high unit pressure)	X			
Corrosive Wear Particles	X			
Oxides Particles (includes rust)		X		
Dark Metallo-oxide Particles (typical hard steels)		X		
Non-ferrous Metallic	X			
Non-metallic, Crystalline		X		
Non-metallic, Amorphous (i.e. friction polymer)	X			

Considered Judgement of Wear Situation

	Very Low		Normal		Caution		Very High (Red Alert)

Emission Spectrometer PPM

Al	Fe	Cr	Ag	Cu	Sn	Mg	Ti	Ni	Si

Comments:

FERROGRAM ANALYSIS REPORT

Ferrogram No.: F1612 Date: 7/5/77

Organization: TTCP Helicopter Sample No.: #11

Equip. Type: gear box Serial No.: Operating Time: 45 hrs.

Sample Date: Oil Type OEP 215 mineral Time on Oil:

Replenishment Data: 10:1 dilution

Volume of Sample passed along Ferrogram 2.0 cc

	Entry	54mm	50mm	10mm
Ferrogram Reading (% area covered)	10.0		4.8	0.9

Volume of Entry _____ um^3 Height of Entry Deposit _____ um

Types of Particles	None	Few	Moderate	Heavy
Normal Rubbing Wear		X		
Fatigue Chunks (Typical gear surface fatigue)	X			
Spheres (fatigue cracks in rolling bearings)	X			
Laminar Particles (gears or rolling bearings)	X			
Severe Wear Particles		X		
Cutting Wear Particles (high unit pressure)	X			
Corrosive Wear Particles	X			
Oxides Particles (includes rust)		X		
Dark Metallo-oxide Particles (typical hard steels)	X			
Non-ferrous Metallic	X			
Non-metallic, Crystalline		X		
Non-metallic, Amorphous (i.e. friction polymer)	X			

Considered Judgement of Wear Situation

	Very Low		Normal		Caution		Very High (Red Alert)

Emission Spectrometer PPM

Al	Fe	Cr	Ag	Cu	Sn	Mg	Ti	Ni	Si

Comments: _____

PHOTO NO. F1601-1 DATE 7/7/77

MAGNIFICATION: 615X

LOCATION ON FERROGRAM: entry

SAMPLE IDENTIFICATION:

Sample #1

OPERATING HISTORY:

0.33 hrs. on oil

REMARKS:

Low amount of normal rubbing wear, severe wear particles. A large nonmetallic particle visible.

PHOTO NO. F1602-1 DATE 7/7/77

MAGNIFICATION: 615X

LOCATION ON FERROGRAM: entry

SAMPLE IDENTIFICATION:

Sample #2

OPERATING HISTORY:

1 hr. on oil

REMARKS:

Particle density increasing to moderate amount of normal rubbing wear and severe wear particles.

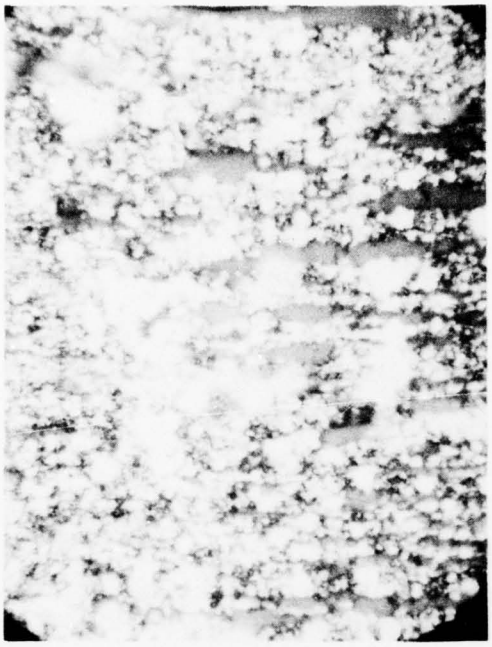

PHOTO NO. F1603-1 DATE 7/8/77

MAGNIFICATION: 615X

LOCATION ON FERROGRAM: entry

SAMPLE IDENTIFICATION:

Sample #3

OPERATING HISTORY:

5 hrs. on oil

REMARKS:

Particle density has increased to heavy amount of normal rubbing wear plus severe wear particles.

PHOTO NO. F1603-2 DATE 7/8/77

MAGNIFICATION: 615X

LOCATION ON FERROGRAM: edge of entry

SAMPLE IDENTIFICATION:

Sample #3

OPERATING HISTORY:

5 hrs. on oil

REMARKS:

View of edge of entry area showing larger severe wear particles - blue oxide temper color visible.

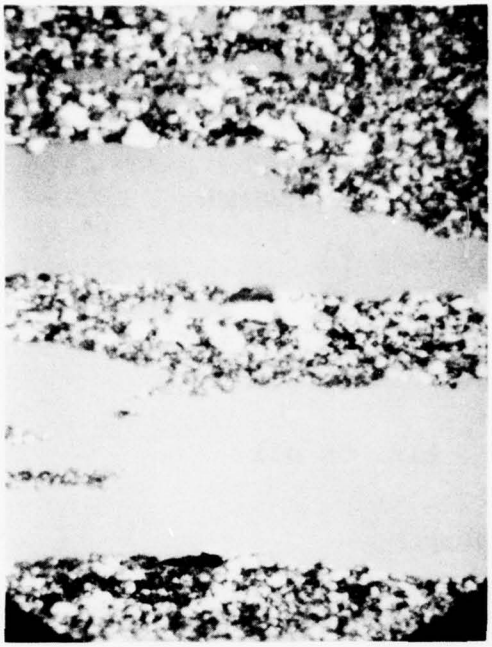

PHOTO NO. F1605-1 DATE 7/8/77

MAGNIFICATION: 400X

LOCATION ON FERROGRAM: entry

SAMPLE IDENTIFICATION:

Sample #5

OPERATING HISTORY:

15 hours on oil

REMARKS:

Amount and size of particle decreasing (compared to Sample #3). Blue oxide temper color on some particles still visible.

PHOTO NO. F1606-1 DATE 7/8/77

MAGNIFICATION: 400X

LOCATION ON FERROGRAM: entry

SAMPLE IDENTIFICATION:

Sample #6

OPERATING HISTORY:

20 hours on oil

REMARKS:

Amount and size of wear particles now diminished to a low level.

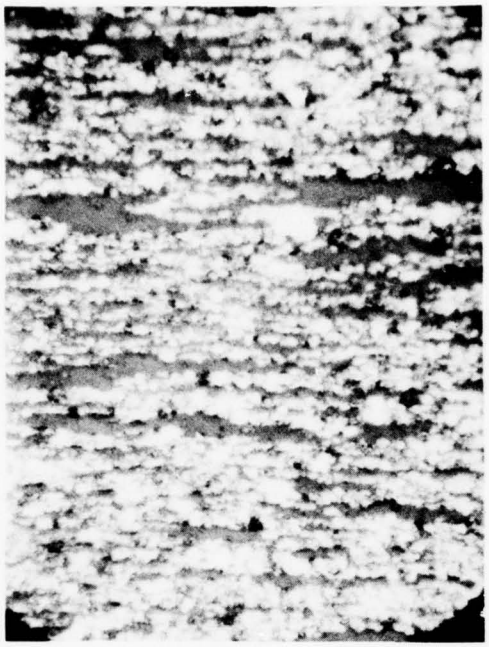

PHOTO NO. F1610-1 DATE 7/8/77

MAGNIFICATION: 615X

LOCATION ON FERROGRAM: entry

SAMPLE IDENTIFICATION:

Sample #10

OPERATING HISTORY:

40 hours on oil

REMARKS:

Normal rubbing wear, some severe wear particles. Deposit of fine nonmetallic particles.

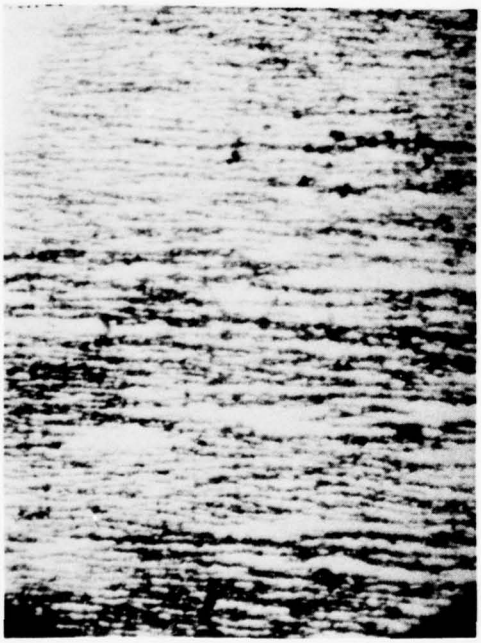

PHOTO NO. F1610-2 DATE 7/8/77

MAGNIFICATION: 400X

LOCATION ON FERROGRAM: entry

SAMPLE IDENTIFICATION:

Sample #10

OPERATING HISTORY:

40 hrs. on oil

REMARKS:

Photo in Bichromatic light shows differences in metallic deposit and fine nonmetallic particles in background.

FERROGRAPHIC ANALYSIS

SECTION TWO

AUSTRALIAN RESEARCH LABORATORIES

TTCP - SUBGROUP P

ACTION GROUP 4

Cooperative Oil Exchange Programme

Samples for Ferrograph Analysis

Enclosed are 4 oil samples taken from the A.R.L. gear rig. These represent a continuation of the previous test, samples from which were taken at 40, 90 and 140 hours respectively. (The results of that test were the subject of an earlier report.)

SAMPLE No. 1 — Unused mineral oil, no additives, 0.45 micron filter.

SAMPLE NO. 2 — This sample was taken after 60 hours of continuous operation.

3000 mls of clean filtered oil was supplied to a clean rig at the commencement of the test.

There was no oil loss or addition during the test.

Total operation time of the gears when the oil was sampled was 200 hours.

SAMPLE NO. 3 — This sample was taken after 100 hours of continuous operation.

3000 mls of clean filtered oil was supplied to a olean rig at the commencement of the test.

There was no oil loss or addition during the test.

Total operation time of the gears when the oil was sampled was 300 hours.

SAMPLE NO. 4 — This sample was taken after 100 hours of continuous operation.

3000 mls of clean filtered oil was supplied to a clean rig at the commencement of the test.

There was no oil loss or addition during the test.

Total operation time of the gears stem the oil was sampled was 400 hours.

Alex Ritchie

FERROGRAPHIC ANALYSIS REPORT

This is a continuation of a previous test reported by us on 9 September 1976. Table I in the previous report is included here for comparative purposes. The severity of wear index continues on an apparently downward curve with increasing time and major gear damage occurred in the first 40 hours. Again, while the density of particles is low, the morphology of the particles still indicates a condition of caution. The ratio of severe wear particles and oxides to normal rubbing wear is high and not expected in a normal wear situation.

Evidence was found of the previously reported plastic contamination that occurred in the first three samples.

TABLE I

ARL Sample	Ferrogram	Photo	Readings (% Area) A_L Entry	A_S 50 mm	A_S 10 mm	Severity of Wear Index $I_S = A_L^2 - A_S^2$
0	1301	1301-1	0.8	0.0	0.0	-----
40	1317	1317-2	57.3	28.7	25.9	2459
90	1318	1318-3	18.7	18.3	9.2	15
140	1319	1319-4	10.9	3.8	7.1	104

$A_L \equiv$ Percent area covered (1 mm dia) at entry deposit (steel particles >5 um across)

$A_S \equiv$ Percent area covered at 50 mm (steel particles range 1 to 2 um across)

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TABLE II

(re: Table I -- 9 Sept. 76)

ARL SAMPLE (HRS.)	FERROGRAM NO.	PHOTO NO.	READINGS (% AREA) A_L Entry	A_S 50 mm	A_S 10 mm	SEVERITY OF WEAR INDEX $I_S = A_L^2 - A_S^2$
Fresh Oil	F1596	F1596-1	---	---	---	
200 hrs.	F1597	F1597-1	9.1	1.8	5.4	80
300 hrs.	F1598	F1598-1	7.8	0.9	3.7	60
400 hrs.	F1599	F1599-1	6.7	1.8	2.7	42

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FERROGRAM ANALYSIS REPORT

Ferrogram No.: F1596 Date: 7/5/77

Organization: TTCP (ARL) Sample No.: No. 1

Equip. Type: ARL test rig Serial No.: Operating Time: 140 hrs.

Sample Date: Oil Type Mineral Time on Oil: -0-

Replenishment Data: no dilution

Volume of Sample passed along Ferrogram 2.0 cc Entry 54mm 50mm 10mm

Ferrogram Reading (% area covered) ____ ____ ____ ____

Volume of Entry _____ um^3 Height of Entry Deposit _____ um

Types of Particles	None	Few	Moderate	Heavy
Normal Rubbing Wear	X			
Fatigue Chunks (Typical gear surface fatigue)	X			
Spheres (fatigue cracks in rolling bearings)	X			
Laminar Particles (gears or rolling bearings)	X			
Severe Wear Particles	X			
Cutting Wear Particles (high unit pressure)	X			
Corrosive Wear Particles	X			
Oxides Particles (includes rust)	X			
Dark Metallo-oxide Particles (typical hard steels)	X			
Non-ferrous Metallic		X(1)		
Non-metallic, Crystalline	X			
Non-metallic, Amorphous (i.e. friction polymer)		X		

Considered Judgement of Wear Situation

	Very Low		Normal		Caution		Very High (Red Alert)

Emission Spectrometer PPM	Al	Fe	Cr	Ag	Cu	Sn	Mg	Ti	Ni	Si

Comments: (1) one isolated piece, very clean sample

FERROGRAM ANALYSIS REPORT

Ferrogram No.: F1597 Date: 7/5/77

Organization: TTCP (ARL) Sample No.: No. 2

Equip. Type: ARL test rig Serial No.: Operating Time: 200 hrs.

Sample Date: Oil Type mineral Time on Oil: 60 hrs.

Replenishment Data: 10:1 dilution

Volume of Sample passed along Ferrogram 2.0 cc

	Entry	54mm	50mm	10mm
Ferrogram Reading (% area covered)	9.1		1.8	5.4

Volume of Entry _____ um^3 Height of Entry Deposit _____ um

Types of Particles	None	Few	Moderate	Heavy
Normal Rubbing Wear		X		
Fatigue Chunks (Typical gear surface fatigue)	X			
Spheres (fatigue cracks in rolling bearings)	X			
Laminar Particles (gears or rolling bearings)	X			
Severe Wear Particles		X		
Cutting Wear Particles (high unit pressure)	X			
Corrosive Wear Particles	X			
Oxides Particles (includes rust)		X		
Dark Metallo-oxide Particles (typical hard steels)		X		
Non-ferrous Metallic	X			
Non-metallic, Crystalline		X		
Non-metallic, Amorphous (i.e. friction polymer)	X			

Considered Judgement of Wear Situation

	Very Low		Normal	X	Caution		Very High (Red Alert)

Emission Spectrometer PPM

Al	Fe	Cr	Ag	Cu	Sn	Mg	Ti	Ni	Si

Comments: _____

FERROGRAM ANALYSIS REPORT

Ferrogram No.: F1598 Date: 7/5/77

Organization: TTCP (ARL) Sample No.: No. 3

Equip. Type: ARL test rig Serial No.: Operating Time: 300 hrs.

Sample Date: Oil Type mineral Time on Oil: 100 hrs.

Replenishment Data: 10:1 dilution

Volume of Sample passed along Ferrogram 2.0 cc

	Entry	54mm	50mm	10mm
Ferrogram Reading (% area covered)	7.8		0.9	3.7

Volume of Entry _____ um^3 Height of Entry Deposit _____ um

Types of Particles	None	Few	Moderate	Heavy
Normal Rubbing Wear		X		
Fatigue Chunks (Typical gear surface fatigue)	X			
Spheres (fatigue cracks in rolling bearings)		X		
Laminar Particles (gears or rolling bearings)	X			
Severe Wear Particles		X		
Cutting Wear Particles (high unit pressure)	X			
Corrosive Wear Particles	X			
Oxides Particles (includes rust)		X		
Dark Metallo-oxide Particles (typical hard steels)		X		
Non-ferrous Metallic	X			
Non-metallic, Crystalline		X		
Non-metallic, Amorphous (i.e. friction polymer)	X			

Considered Judgement of Wear Situation

	Very Low		Normal	X	Caution		Very High (Red Alert)

Emission Spectrometer PPM

Al	Fe	Cr	Ag	Cu	Sn	Mg	Ti	Ni	Si

Comments: _____

FERROGRAM ANALYSIS REPORT

Ferrogram No.: F1599 Date: 7/5/77

Organization: TTCP ARL Sample No.: No. 4

Equip. Type: ARL test rig Serial No.: Operating Time: 400 hrs.

Sample Date: Oil Type mineral Time on Oil: 200 hrs.

Replenishment Data: 10:1 dilution

Volume of Sample passed along Ferrogram 2.0 cc

	Entry	54mm	50mm	10mm
Ferrogram Reading (% area covered)	6.7		1.8	2.7

Volume of Entry _____ um^3 Height of Entry Deposit _____ um

Types of Particles	None	Few	Moderate	Heavy
Normal Rubbing Wear		X		
Fatigue Chunks (Typical gear surface fatigue)	X			
Spheres (fatigue cracks in rolling bearings)		X		
Laminar Particles (gears or rolling bearings)	X			
Severe Wear Particles		X		
Cutting Wear Particles (high unit pressure)	X			
Corrosive Wear Particles	X			
Oxides Particles (includes rust)		X		
Dark Metallo-oxide Particles (typical hard steels)		X		
Non-ferrous Metallic	X			
Non-metallic, Crystalline			X	
Non-metallic, Amorphous (i.e. friction polymer)		X		

Considered Judgement of Wear Situation

	Very Low		Normal	X	Caution		Very High (Red Alert)

Emission Spectrometer PPM

Al	Fe	Cr	Ag	Cu	Sn	Mg	Ti	Ni	Si

Comments: _____

PHOTO NO. F1596-1 DATE 7/5/77

MAGNIFICATION: 400X

LOCATION ON FERROGRAM: entry

SAMPLE IDENTIFICATION:

ARL unused oil

OPERATING HISTORY:

none

REMARKS:

Oil generally quite clean except for this piece of amorphous material and piece of isolated metal.

PHOTO NO. F1597-1 DATE 7/14/77

MAGNIFICATION: 615X

LOCATION ON FERROGRAM: entry

SAMPLE IDENTIFICATION:

RL #2

OPERATING HISTORY:

Time on oil: 60 hrs.

Time on engine: 200 hrs.

REMARKS:

The bulk of Ferrogram deposit was found in entry area. Normal rubbing wear, severe wear oxides and heavy deposit of plastic material.

PHOTO NO. F1597-2 DATE 7/14/7

MAGNIFICATION: 615X

LOCATION ON FERROGRAM: entry

SAMPLE IDENTIFICATION:

ARL #2

OPERATING HISTORY:

Time on oil: 60 hrs.

Time on engine: 200 hrs.

REMARKS:
Polarized light photo showing plastic particles.

PHOTO NO. F1597-3 DATE 7/14/7

MAGNIFICATION: 615X

LOCATION ON FERROGRAM: entry

SAMPLE IDENTIFICATION:

ARL #2

OPERATING HISTORY:
same as above

REMARKS:

Bichromatic light showing metallic particles (red), plastic particles translucent.

PHOTO NO. F1598-1 DATE 7/14/77

MAGNIFICATION: 615X

LOCATION ON FERROGRAM: entry

SAMPLE IDENTIFICATION:

ARL #3

OPERATING HISTORY:

Time on oil: 100 hrs.

Time on engine: 300 hrs.

REMARKS:

Bichromatic photo showing metallic deposit red plas deposit translucent.

PHOTO NO. F1599-1 DATE 7/14/77

MAGNIFICATION: 615X

LOCATION ON FERROGRAM: entry

SAMPLE IDENTIFICATION:

ARL #4

OPERATING HISTORY:

Time on oil: 200 hrs.

Time on engine 400 hrs.

REMARKS:

Bichromatic photo showing metallic deposit red, plastic deposit translucent.

FERROGRAPHIC ANALYSIS

SECTION THREE

DEPARTMENT OF THE NAVY
OFFICE OF NAVAL RESEARCH
WASHINGTON, D. C.

TTCP(P1) WORKING PARTY RE: FAILURE MECHANISMS IN OIL-LUBRICATED MACHINERY

DRIP OIL SAMPLES FROM HELICOPTER TRANSMISSION

Sample	Running time-hrs
1	1
2	77
3	130
4	155

plus unused oil sample

Capacity: 20 liters

Lube Oil Specification: MIL-L-23699B
NATO O-156

Note: These samples are not representative of an actual failure. They are forwarded for the purpose of examining the wear mode(s) involved and wear progression. A later set is anticipated which will be representative of a similar unit removed because of excessive vibration and an excessive wear indication.

Foxboro/Trans-Sonics, Inc.

FERROGRAPHIC ANALYSIS REPORT

SUBJECT: TTCP (P-1) Working Party re: Failure Mechanisms in Oil Lubricated Machinery
DREP Oil Samples from Helicopter Transmission
(copy of memo attached)

SAMPLE NO.	RUNNING TIME HOURS	FERROGRAM NO.	FERROGRAM READINGS (% AREA COVERED) ENTRY	50 mm	10 mm	
Fresh oil	-0-	F1545	-0-	-0-	-0-	
#1	1	F1546	45.3	44.2	44.9	98
#2	77	F1547	9.6	2.1	7.1	88
#3	130	F1548	30.0	27.5	15.8	144
#4	150	F1549	18.0	19.0	21.9	-37 not meaningful

Ferrogram readings show variations in the amount of deposit with the largest amount found on F1546 (sample #1) after one hour of operation then declining amounts with a light deposit (sample #2), fairly heavy deposit (sample #3) then finally to a moderate amount in sample #4.

The deposits were chiefly normal rubbing wear with some severe wear particles and small amounts of oxides. The Ferrograms were made from undiluted oil samples.

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FERROGRAM ANALYSIS REPORT

Ferrogram No.: F1545 Date: 4/29/77

Organization: TTCP (P-1) Sample No.: Unused

Equip. Type: Helicopter transmission Serial No.: Operating Time:

Sample Date: Oil Type Mil-L-23699B Time on Oil: -0-

Replenishment Data: not diluted

Volume of Sample passed along Ferrogram 2.0 cc

Ferrogram Reading (% area covered)	Entry	54mm	50mm	10mm
	-0-(1)		-0-	-0-

Volume of Entry _____ um^3 Height of Entry Deposit _____ um

Types of Particles	None	Few	Moderate	Heavy
Normal Rubbing Wear	X			
Fatigue Chunks (Typical gear surface fatigue)	X			
Spheres (fatigue cracks in rolling bearings)	X			
Laminar Particles (gears or rolling bearings)	X			
Severe Wear Particles	X			
Cutting Wear Particles (high unit pressure)	X			
Corrosive Wear Particles	X			
Oxides Particles (includes rust)	X			
Dark Metallo-oxide Particles (typical hard steels)	X			
Non-ferrous Metallic	X			
Non-metallic, Crystalline		X		
Non-metallic, Amorphous (i.e. friction polymer)	X			

Considered Judgement of Wear Situation

	Very Low		Normal		Caution		Very High (Red Alert)

Emission Spectrometer PPM	Al	Fe	Cr	Ag	Cu	Sn	Mg	Ti	Ni	Si

Comments: (1) No Ferrogram readings - substrate very clean

FERROGRAM ANALYSIS REPORT

Ferrogram No.: F1546 Date: 4/29/77

Organization: TTCP (P-1) Sample No.: 1

Equip. Type: Helicopter Transmission Serial No.: Operating Time: 1 hr.

Sample Date: Oil Type Mil-L-23699B Time on Oil: 1 hr.

Replenishment Data: not diluted

Volume of Sample passed along Ferrogram 2.0 cc

	Entry	54mm	50mm	10mm
Ferrogram Reading (% area covered)	45.3		44.2	44.9

Volume of Entry _____ um^3 Height of Entry Deposit _____ um

Types of Particles	None	Few	Moderate	Heavy
Normal Rubbing Wear				X
Fatigue Chunks (Typical gear surface fatigue)		X		
Spheres (fatigue cracks in rolling bearings)	X			
Laminar Particles (gears or rolling bearings)	X			
Severe Wear Particles		X		
Cutting Wear Particles (high unit pressure)	X			
Corrosive Wear Particles	X			
Oxides Particles (includes rust)		X		
Dark Metallo-oxide Particles (typical hard steels)	X			
Non-ferrous Metallic		X		
Non-metallic, Crystalline		X		
Non-metallic, Amorphous (i.e. friction polymer)	X			

Considered Judgement of Wear Situation

	Very Low		Normal		Caution		Very High (Red Alert)

Emission Spectrometer PPM	Al	Fe	Cr	Ag	Cu	Sn	Mg	Ti	Ni	Si

Comments: _____

FERROGRAM ANALYSIS REPORT

Ferrogram No.: F1547 Date: 4/29/77

Organization: TTCP (P-1) Sample No.: 2

Equip. Type: Helicopter Transmission Serial No.: Operating Time: 77 hrs.

Sample Date: Oil Type Mil-L-23699B Time on Oil: 77 hrs.

Replenishment Data: not diluted

Volume of Sample passed along Ferrogram 2.0 cc

	Entry	54mm	50mm	10mm
Ferrogram Reading (% area covered)	9.6(1)		2.1	7.1

Volume of Entry _____ um^3 Height of Entry Deposit _____ um

Types of Particles	None	Few	Moderate	Heavy
Normal Rubbing Wear			X	
Fatigue Chunks (Typical gear surface fatigue)	X			
Spheres (fatigue cracks in rolling bearings)	X			
Laminar Particles (gears or rolling bearings)	X			
Severe Wear Particles		X		
Cutting Wear Particles (high unit pressure)	X			
Corrosive Wear Particles	X			
Oxides Particles (includes rust)		X		
Dark Metallo-oxide Particles (typical hard steels)	X			
Non-ferrous Metallic		X		
Non-metallic, Crystalline			X	
Non-metallic, Amorphous (i.e. friction polymer)	X			

Considered Judgement of Wear Situation

	Very Low		Normal		Caution		Very High (Red Alert)

Emission Spectrometer PPM

Al	Fe	Cr	Ag	Cu	Sn	Mg	Ti	Ni	Si

Comments: (1) reading of 9.6 partly caused by large pieces of nonmetallic debris - entry area away from the debris 5.1

FERROGRAM ANALYSIS REPORT

Ferrogram No.: F1548 Date: 4/29/77

Organization: TTCP (P-1) Sample No.: 3

Equip. Type: Helicopter Transmission Serial No.: _____ Operating Time: 130 hrs.

Sample Date: _____ Oil Type Mil-L-23699B Time on Oil: 130 hrs.

Replenishment Data: not diluted

Volume of Sample passed along Ferrogram 2.0 cc

	Entry	54mm	50mm	10mm
Ferrogram Reading (% area covered)	30.0		27.5	15.8

Volume of Entry _____ um^3 Height of Entry Deposit _____ um

Types of Particles	None	Few	Moderate	Heavy
Normal Rubbing Wear				X
Fatigue Chunks (Typical gear surface fatigue)	X			
Spheres (fatigue cracks in rolling bearings)	X			
Laminar Particles (gears or rolling bearings)				
Severe Wear Particles		X		
Cutting Wear Particles (high unit pressure)	X			
Corrosive Wear Particles	X			
Oxides Particles (includes rust)		X		
Dark Metallo-oxide Particles (typical hard steels)	X			
Non-ferrous Metallic		X		
Non-metallic, Crystalline		X		
Non-metallic, Amorphous (i.e. friction polymer)	X			

Considered Judgement of Wear Situation

	Very Low		Normal		Caution		Very High (Red Alert)

Emission Spectrometer PPM

Al	Fe	Cr	Ag	Cu	Sn	Mg	Ti	Ni	Si

Comments: _____

FERROGRAM ANALYSIS REPORT

Ferrogram No.: F1549 Date: 4/29/77

Organization: TTCP (P-1) Sample No.: 4

Equip. Type: Helicopter Transmission Serial No.: _____ Operating Time: 155 hrs.

Sample Date: _____ Oil Type Mil-L-23699B Time on Oil: 155 hrs.

Replenishment Data: not diluted

Volume of Sample passed along Ferrogram 2.0 cc

	Entry	54mm	50mm	10mm
Ferrogram Reading (% area covered)	18.0	___	19.1	21.9

Volume of Entry _____ um^3 Height of Entry Deposit _____ um

Types of Particles	None	Few	Moderate	Heavy
Normal Rubbing Wear			X	
Fatigue Chunks (Typical gear surface fatigue)	X			
Spheres (fatigue cracks in rolling bearings)	X			
Laminar Particles (gears or rolling bearings)				
Severe Wear Particles		X		
Cutting Wear Particles (high unit pressure)	X			
Corrosive Wear Particles	X			
Oxides Particles (includes rust)		X		
Dark Metallo-oxide Particles (typical hard steels)	X			
Non-ferrous Metallic		X		
Non-metallic, Crystalline		X		
Non-metallic, Amorphous (i.e. friction polymer)	X			

Considered Judgement of Wear Situation

	Very Low		Normal		Caution		Very High (Red Alert)

Emission Spectrometer PPM

Al	Fe	Cr	Ag	Cu	Sn	Mg	Ti	Ni	Si

Comments: _____

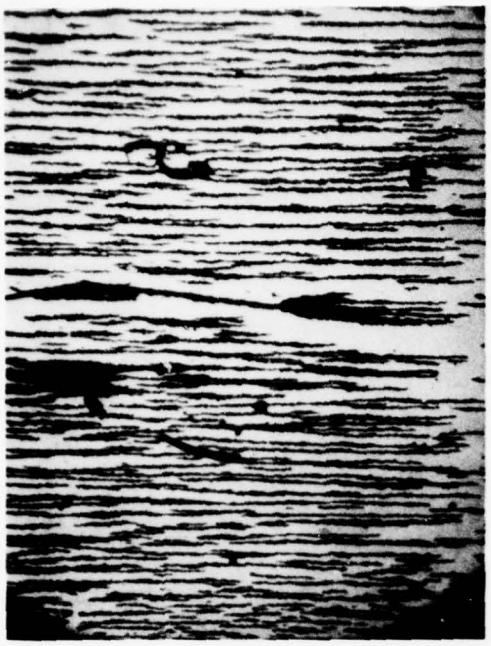


PHOTO NO. F1546-1 DATE 5/21/77

MAGNIFICATION: 100X

LOCATION ON FERROGRAM: entry

SAMPLE IDENTIFICATION:

TTCP Sample #1

OPERATING HISTORY:
Time on oil: 1 hour

REMARKS:

General view of entry area

PHOTO NO. F1546-2 DATE 5/21/77

MAGNIFICATION: 615X

LOCATION ON FERROGRAM: entry area

SAMPLE IDENTIFICATION:

TTCP sample #1

OPERATING HISTORY:

Time on oil: 1 hour

REMARKS:

Enlarged view of photo F1546-1 above. Normal rubbing wear, some severe wear particles and nonmetallic debris

PHOTO NO. F1547-1 DATE 5/21/77

MAGNIFICATION: 100X

LOCATION ON FERROGRAM: entry area

SAMPLE IDENTIFICATION:

TTCP sample #2

OPERATING HISTORY:

Time on oil: 77 hours

REMARKS:

General view of entry area

PHOTO NO. F1547-2 DATE 5/21/77

MAGNIFICATION: 615X

LOCATION ON FERROGRAM: entry area

SAMPLE IDENTIFICATION:

TTCP sample #2

OPERATING HISTORY:
Time on oil: 77 hours

REMARKS:
Bichromatic light photo. Shows normal rubbing wear together with deposit of fine transparent oxides

PHOTO NO. F1548-1 DATE 7/5/77

MAGNIFICATION: 100X

LOCATION ON FERROGRAM: entry

SAMPLE IDENTIFICATION:

TTCP (P-1)
Sample #3

OPERATING HISTORY:

Time on oil: 130 hours

REMARKS:
General view of entry area. Particles are chiefly normal rubbing wear.

PHOTO NO. F1548-2 DATE 7/5/77

MAGNIFICATION: 615X

LOCATION ON FERROGRAM: entry

SAMPLE IDENTIFICATION:
TTCP (P-1)
Sample #3

OPERATING HISTORY:

Time on oil: 130 hours

REMARKS:

Enlarged view of F1548-1 above showing normal rubbing wear plus some severe wear particles

PHOTO NO. F1549-1 DATE 7/5/77

MAGNIFICATION: 100X

LOCATION ON FERROGRAM: entry

SAMPLE IDENTIFICATION:
TTCP (P-1)
Sample #4

OPERATING HISTORY:

Time on oil: 155 hours

REMARKS:
General view of entry area. Metallic deposit chiefly normal rubbing wear

PHOTO NO. F1549-2 DATE 7/5/77

MAGNIFICATION: 615X

LOCATION ON FERROGRAM: entry

SAMPLE IDENTIFICATION:

TTCP (P-1)
sample #4

OPERATING HISTORY:

Time on oil: 155 hours

REMARKS:
Enlarged view of photo F1549-1 above. Some severe wear particles visible

FERROGRAPHIC ANALYSIS

SECTION FOUR

NAVAL AIR ENGINEERING CENTER
LAKEHURST, NEW JERSEY

Foxboro/Trans-Sonics, Inc.

14 July 77

FERROGRAPHIC ANALYSIS REPORT

SUBJECT: The Technical Cooperation Program (TTCP Working Party on the Characterization of Wear in Oil Lubricated Samples

Three separate oil samples were provided by the Naval Air Engineering Center, Lakehurst, N.J. They are identified as having been obtained from oil wetted component bench test. The respective test information is provided for each sample in a copy of Enclosure (2) "Component Test Descriptions" attached.

The samples are labeled respectively RY115 (sump), Failed Bearing #007, and G.I. test #9. A standard Ferrogram Analysis Report and appropriate photographs are provided for each test.

FOXBORO

FERROGRAM ANALYSIS REPORT

Ferrogram No.: F1550 Date: 4/30/77

Organization: TTCP Sample No.: RY115 (sump)

Equip. Type: _____ Serial No.: _____ Operating Time: _____

Sample Date: _____ Oil Type _____ Time on Oil: _____

Replenishment Data: not diluted

Volume of Sample passed along Ferrogram 2.0 cc

	Entry	54mm	50mm	10mm
Ferrogram Reading (% area covered)	33.1		18.4	6.3

Volume of Entry _____ um^3 Height of Entry Deposit _____ um

Particle Height 30 Pm 9 Pm Fe

$4,445.7 \times 10^4$ 72 μm.

Types of Particles	None	Few	Moderate	Heavy
Normal Rubbing Wear				X
Fatigue Chunks (Typical gear surface fatigue)	X			
Spheres (fatigue cracks in rolling bearings)	X			
Laminar Particles (gears or rolling bearings)	X			
Severe Wear Particles			X	
Cutting Wear Particles (high unit pressure)	X			
Corrosive Wear Particles		X		
Oxides Particles (includes rust)		X		
Dark Metallo-oxide Particles (typical hard steels)		X		
Non-ferrous Metallic	X			
Non-metallic, Crystalline		X		
Non-metallic, Amorphous (i.e. friction polymer)	X			

Considered Judgement of Wear Situation

	Very Low		Normal		Caution		Very High (Red Alert)

Emission Spectrometer PPM

Al	Fe	Cr	Ag	Cu	Sn	Mg	Ti	Ni	Si

Comments: Some blue oxide temper color showing

FERROGRAM ANALYSIS REPORT

Ferrogram No.: F1551 Date: 4/30/77

Organization: TTCP Sample No.: GI test #9

Equip. Type: _____ Serial No.: _____ Operating Time: 112 hrs

Sample Date: _____ Oil Type _____ Time on Oil: _____

Replenishment Data: not diluted

Volume of Sample passed along Ferrogram 2.0 cc

	Entry	54mm	50mm	10mm
Ferrogram Reading (% area covered)	12.0		5.1	1.8

Volume of Entry _____ um^3 Height of Entry Deposit _____ um

PS → 3P1/μm Fe

2.8 (1/2)^4 > 20 μm in 100 cc

Types of Particles	None	Few	Moderate	Heavy
Normal Rubbing Wear			X	
Fatigue Chunks (Typical gear surface fatigue)	X			
Spheres (fatigue cracks in rolling bearings)	X			
Laminar Particles (gears or rolling bearings)	X			
Severe Wear Particles		X		
Cutting Wear Particles (high unit pressure)	X			
Corrosive Wear Particles				
Oxides Particles (includes rust)		X		
Dark Metallo-oxide Particles (typical hard steels)				
Non-ferrous Metallic	X			
Non-metallic, Crystalline		X		
Non-metallic, Amorphous (i.e. friction polymer)	X			

Considered Judgement of Wear Situation

	Very Low		Normal		Caution		Very High (Red Alert)

Emission Spectrometer PPM

Al	Fe	Cr	Ag	Cu	Sn	Mg	Ti	Ni	Si

Comments: _____

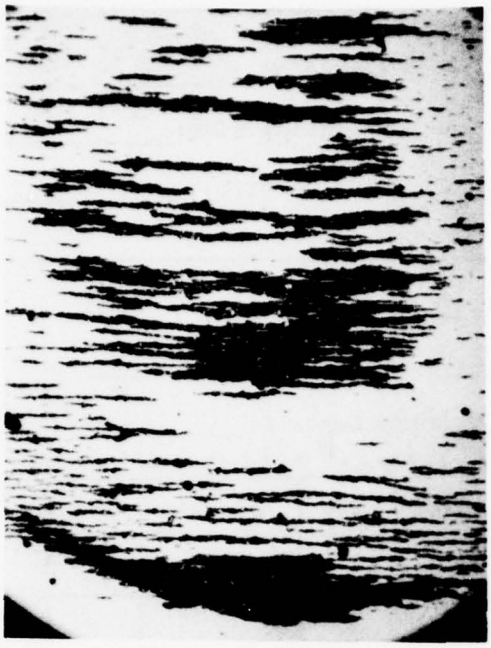


PHOTO NO. F1550-1 DATE 7/5/77

MAGNIFICATION: 100X

LOCATION ON FERROGRAM: entry

SAMPLE IDENTIFICATION:

RY115
(sump)

OPERATING HISTORY:

Re: enclosure # 2

REMARKS:

General view of entry area, chiefly normal rubbing wear and severe wear particles

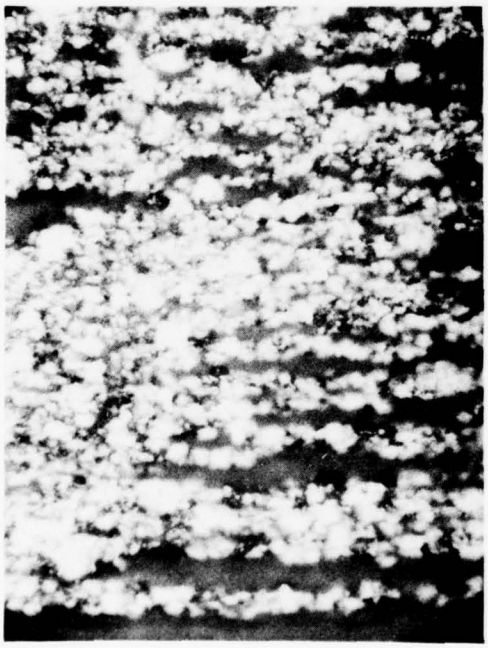


PHOTO NO. F1550-2 DATE 7/5/77

MAGNIFICATION: 615X

LOCATION ON FERROGRAM: entry

SAMPLE IDENTIFICATION:

RY 115
(sump)

OPERATING HISTORY:

Re enclosure #2

REMARKS:

Enlarged view of photo F1550-1 above

FERROGRAM ANALYSIS REPORT

Ferrogram No.: F1552 Date: 4/30/77

Organization: TTCP Sample No.: Failed Bearing #007

Equip. Type: _____ Serial No.: _____ Operating Time: _____

Sample Date: _____ Oil Type _____ Time on Oil: _____

Replenishment Data: _____

Volume of Sample passed along Ferrogram 2.0 cc

Ferrogram Reading (% area covered)	Entry	54mm	50mm	10mm
	4.3		3.5	0.9

Volume of Entry _____ um^3 Height of Entry Deposit _____ um

Count = 8 2 x 0.2 x 2.4 µm To = 1.4 µm Total Σ

Types of Particles	None	Few	Moderate	Heavy
Normal Rubbing Wear		X		
Fatigue Chunks (Typical gear surface fatigue)				
Spheres (fatigue cracks in rolling bearings)		X(1)		
Laminar Particles (gears or rolling bearings)		X		
Severe Wear Particles				
Cutting Wear Particles (high unit pressure)	X			
Corrosive Wear Particles	X			
Oxides Particles (includes rust)		X		
Dark Metallo-oxide Particles (typical hard steels)	X			
Non-ferrous Metallic		X(2)		
Non-metallic, Crystalline		X		
Non-metallic, Amorphous (i.e. friction polymer)	X			

Considered Judgement of Wear Situation

	Very Low		Normal		Caution		Very High (Red Alert)

Emission Spectrometer PPM

Al	Fe	Cr	Ag	Cu	Sn	Mg	Ti	Ni	Si

Comments: (1) one sphere only (2) pieces of nonferrous metallic particles present - thought to be brass. Laminar particle visible.

PHOTO NO. F1551-1 DATE 7/5/77

MAGNIFICATION: 100X

LOCATION ON FERROGRAM: entry

SAMPLE IDENTIFICATION:

G.I. test #9

OPERATING HISTORY:

Re: enclosure #2

REMARKS:

Normal rubbing wear, severe wear particles and nonmetallic debris

PHOTO NO. F1551-2 DATE 7/5/77

MAGNIFICATION: 615X

LOCATION ON FERROGRAM: entry

SAMPLE IDENTIFICATION:

G.I. test #9

OPERATING HISTORY:

Re enclosure #2

REMARKS:

Enlarged view of photo F1551-1

PHOTO NO. F1552-1 DATE 7/5/77

MAGNIFICATION: 100X

LOCATION ON FERROGRAM: Entry

SAMPLE IDENTIFICATION:

Failed bearing #007

OPERATING HISTORY:

Re: enclosure #2

REMARKS:

General view of entry area

PHOTO NO. F1552-2 DATE 7/5/77

MAGNIFICATION: 615X

LOCATION ON FERROGRAM: Entry

SAMPLE IDENTIFICATION:

Failed bearing #007

OPERATING HISTORY:

Re: enclosure #2

REMARKS:

Enlarged view of photo F1552 above. Laminar particle visible at right.

PHOTO NO. F1551-3 DATE 7/14/77

MAGNIFICATION: 615X

LOCATION ON FERROGRAM: entry

SAMPLE IDENTIFICATION:

G. I. Test #4

OPERATING HISTORY:

Re: enclosure #2

REMARKS:

Bichromatic photo of view in photo #F1551-2.

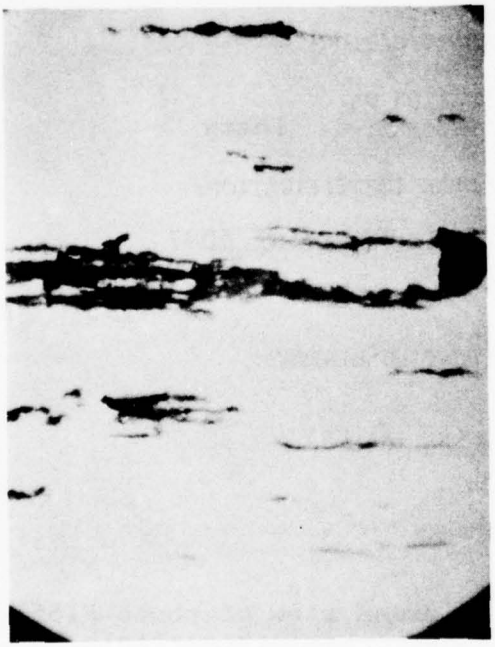


PHOTO NO. F1552-3 DATE 7/14/

MAGNIFICATION: 615X

LOCATION ON FERROGRAM: entry

SAMPLE IDENTIFICATION:

Failed bearing #007

OPERATING HISTORY:

Re: enclosure #2

REMARKS:

Bichromatic photo of view in photo F1552-2

DEPARTMENT OF THE NAVY
NAVAL AIR ENGINEERING CENTER
LAKEHURST, N. J. 08733

IN REPLY REFER TO

92724/22:PBS:dn
13800
25 MAR 1977

From: Commanding Officer, Naval Air Engineering Center

Subj: The Technical Cooperation Program (TTCP) Working Party on the Characterization of Wear in Oil Lubricated Systems; distribution of oil samples

Encl: (1) Component Oil Samples
(2) Component Test Descriptions

1. As per the approach of the TTCP Working Party on the Characterization of Wear in Oil Lubricated Systems, significant oil samples are to be distributed to work party members for analysis.

2. Enclosure (1) contains three oil samples provided by the Naval Air Engineering Center (NAVAIRENGCEN) for analysis under this effort.

3. These samples have been obtained from oil wetted component bench tests performed under the NAVAIRENGCEN Oil Analysis Program. Respective component test information is provided in enclosure (2).

4. An analysis should be performed on these samples by each participant. Analysis results will be compared as discussed in previous working party organizational meetings.

J. J. CONNOR
By direction

Distribution List:
See Page 2

92724/22:PBS:dn
13800

25 MAR 1977

Subj: The Technical Cooperation Program (TTCP) Working Party on the Characterization of Wear in Oil Lubricated Systems; distribution of oil samples

Distribution List

Dr. Geoffrey Pocock
Admirality Materials Lab
Holton Heath Poole Dorset
BH16 6JU
United Kingdom

Lt. Richard S. Miller
Dept of the Navy
Office of Naval Research
Arlington, VA 22217

Mr. Charles P. Merhib
Army Materials and Mechanics Research
Watertown, MA 02172

Mr. P. W. Centers
AFAPL/SFL
Wright-Patterson AFB
Dayton, OH 45433

Mr. Clinton A. Waggoner
Defense Research Establishment Pacific
FMO VOS 1BO
Victoria, British Columbia
Canada

Mr. Max L. Atkin
Aeronautical Research Laboratories
506 Lorimer St. Fishermens Bend
Box 4331 P.O.
Melbourne, Victoria 3001
Australia

Copy to: w/o encl.
NAVAIR (340E)
NAVMAT (033)

COMPONENT TEST

DESCRIPTIONS

ENCLOSURE (2)

GEAR TEST GI OIL SAMPLE

Two test gears were run on a Ryder Research Gear Machine with the objective of reducing scuffing/scoring wear in order to study normal wear/fatigue.

These two gears were AISI 9310 aircraft quality steel, case hardened spur gears with 28 teeth at 22.5 degree pressure angle and eight diametral pitch. The load gear was identical except for tooth width. The gears operated at a 1:1 gear ratio. The gears meet both the metallurgical and dimensional specifications set forth in Test Method D-1947 of the American Society for Testing and Materials. [1]

The arrangement of the gears in the Ryder test head is shown in Illustration 1. The oil system used for the test is shown in Illustration 2.

A qualified military specification oil MIL-L-23699 was used in the test oil system.[2]

The test procedure followed was the following[3]:

1. run test @ 10,000 RPM
2. circulate oil for 10 minutes
3. take oil samples for background reading before and after oil is circulated
4. run-in for 10 minutes at each 40,300 N/m (230 PPI) load increment up to 483,400 N/m (2760 PPI) load; read and record scuff after each load increment
5. if average scuff is less than 10 percent, continue test at constant 483,400 N/m (2760 PPI) load
6. take oil samples every five hours up to thirty hours and every ten hours thereafter until pitting occurs
7. increase load to 523,600 N/m (2990 PPI) at 82 hours total time

---

1 P.J. Mangione, Oil Analysis Program Gear Bench Testing (Trenton, New Jersey, Naval Air Propulsion Test Center, Lube and Power Drive Systems Div., 1976) p. 2.

2 Ibid, Page 2.

3 Ibid. p. 4-5.

8. increase load to 563,900 N/m (3220 PPI) at 102 hours total time

9. test stopped at 112 hours total time

10. oil system drained and oil stored

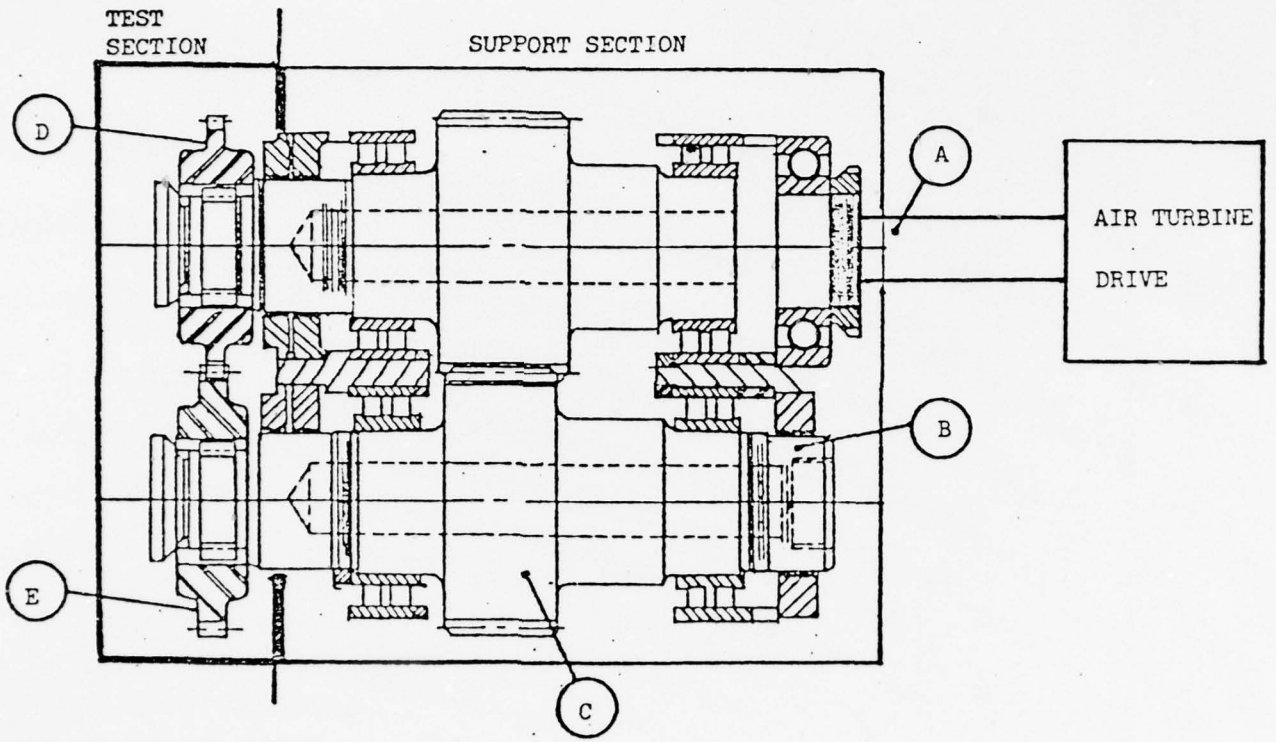
The data recorded from this test is summarized in Illustration 3.

The GI oil sample is part of the oil drainage of step 10 in the test procedure.

The failure modes exhibited by the test gears are summarized in Illustration 3. At 1.2×10^6 revolutions there was mild pitting on two teeth. By 4.2×10^6 revolutions there was mild pitting on three teeth. No other pitting was noticed until 55.2×10^6 revolutions when a large spall developed on a fourth tooth.

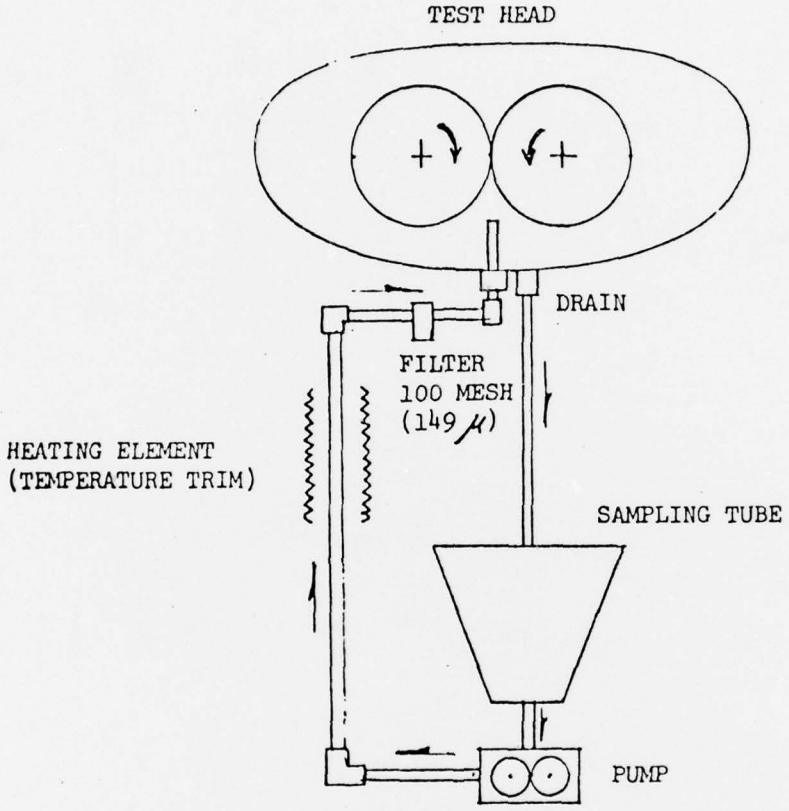
The accompanying gradual increase in average scuff until the test conclusion is recorded in Illustration 3. Note that the cirtical value for scuff failure, according to Mangione, was to be 22.5% average scuff. This failure criteria was not reached during the test. Failure was the large spall.

FIGURE 1. CROSS-SECTION OF RYDER RESEARCH GEAR MACHINE TEST HEAD



A. DRIVE SHAFT
B. DRIVEN (LOAD) SHAFT
C. HELICAL "SLAVE" GEARS
D. TEST GEAR
E. LOAD GEAR

FIGURE 3. SCHEMATIC DIAGRAM OF SKF "CLEAN" CLOSED-LOOP GEAR LUBRICATION SYSTEM



OIL ANALYSIS PROGRAM SUMMARY OF GEAR BENCH TESTS

TYPE TEST	TEST IDENT.	SAMPLE NO.	TOTAL TIME (HRS)	TOTAL REV. ($\times 10^6$)	TOOTH LOAD N/m X 10^3	TOOTH LOAD (PPI)	FAILURE PITS	FAILURE AVG. SCUFF (PERCENT)	NOAP Fe (PPM)	REMARKS
FATIGUE										
	GI-									
TEST GEAR SET NARROW M-1997 WIDE M-1750 "B" SIDE		GI-2455-1	0	0	0	(0)	-	0	1	New oil
		GI-2455-2	0	0	0	(0)	-	0	1	Circulated new oil
		GI-2455-3	1.0	0.6	241.8	(1380)	-	0	1	Load increased from 40,300 to 241,800 N/m (230 to 1380 PPI) in 40,300 N/m (230 PPI) increments (10 min. each).
		GI-2465-4	2.0	1.2	483.4	(2760)	MILD 2 TEETH	1.6	2	Load increased from 241,800 to 483,400 N/m (1380 to 2760 PPI) in 40,300 N/m (230 PPI) increments (10 min. each).
		GI-2475-5	7.0	4.2	483.4	(2760)	MILD 3 TEETH	2	2	Constant load for 5 hours
		GI-2475-6	12.0	7.2	483.4	(2760)	NO CHANGE	2.6	2	
		GI-2485-7	17.0	10.2	483.4	(2760)		3	2	
		GI-2485-8	22.0	13.2	483.4	(2760)		3.7	2	
		GI-2515-9	27.0	16.2	483.4	(2760)		4	2	
		GI-2515-10	32.0	19.2	483.4	(2760)		4.4	2	
		GI-2525-11	42.0	25.2	483.4	(2760)		4.8	2	Constant load for 10 hours
		GI-2535-12	52.0	31.2	483.4	(2760)		5	2	
		GI-2545-13	62.0	37.2	483.4	(2760)		5	3	
		GI-2555-14	72.0	43.2	483.4	(2760)		5.3	2	
		GI-2585-15	82.0	49.2	523.6	(2990)		5.6	3	Load increased to 523,600 N/m (2990 PPI) constant load for 10 hours.
		GI-2595-16	92.0	55.2	523.6	(2990)	4TH TOOTH LARGE SPALL	6.3	3	
		GI-2605-17	102.0	61.2	563.9	(3220)		7	4	Load increased to 563,900 N/m (3220 PPI) constant load for 10 hours
		GI-2615-18	112.0	67.2	563.9	(3220)		7.3	3	

ABORT TEST: NO SIGNIFICANT INCREASE IN FATIGUE PITTING

6 Mangione, P. 23

NAPTC-PE-36

BALL BEARING BS 007 OIL SAMPLE

A ball bearing test was run on the standard SKF R-2 machine shown in Illustration 4. A schematic drawing of the bearing is shown in Illustration 5. The deep-groove ball bearing is made of through-hardening grade AISI 52100 steel. The steel is carbon vacuum de-oxidized bearing quality steel. [7]

This test on ball bearing BS 007 was an endurance test. The oil used in the test was an oil that met military specification MIL-L-23699. Illustration 6 is a schematic of the closed loop lubrication system used in the test. The test parameters for this bearing run are reproduced in Illustration 7.

The as-received oil was filtered through a 3 μm Millipore filter before being used for the test. About two gallons of oil was used to fill the oil reservoir at the start of the test. The amount was not allowed to decrease below 1.5 gallons. This was achieved by adding new oil to the reservoir at recorded intervals. [8]

Twenty samples were taken during this bearing test. They were: [9]

Sample #	1	0.05 million revolutions
	2	39.6
	3	66.0
	4	97.0
	5	151.0
	6	194.0
	7	211.0
	8	239.0
	9	263.0
	10	302.0
	11	320.0
	12	369.0
	13	396.0
	14	423.0
	15	468.0
	16	489.0
	17	495.0
	18	545.0
	19	560.0
	20	573.0

At the finish of this test the oil reservoir was drained and the oil stored. The oil sample ball bearing BS 007 is part of the oil drained from the test system at the conlusion of the test.

The bearing failure was a spalling failure of the inner race at a Vickers

---

7 H. Dalal, Progression of Surface Damage and Oil Wear Debris Accumulation in Rolling Contact Fatigue (King of Prussia, Pennsylvania, SKF Industries, Inc., 1975), p. 3

indentation. The inner race surface was initially dented with a Vickers pyramidal indentor using a 10 kg. load. The indentor has an apex angle of 136° giving a diagonal-to-depth ratio of approximately 4.3/1.[10] The indentation size was determined to be 163 μm.

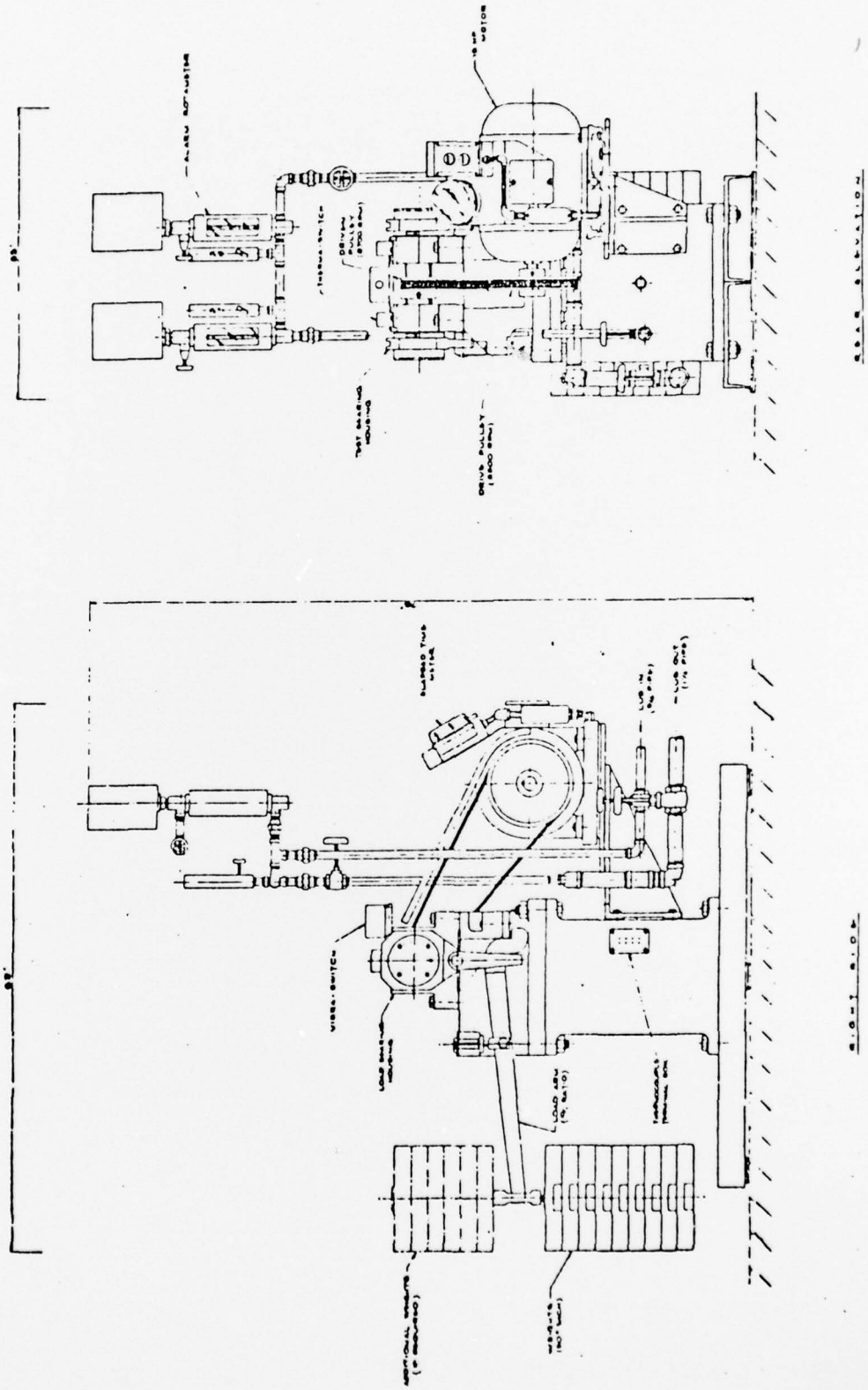
The purpose of the indentation was to promote failure and shorten the time to end of test in this clean system.

---

10 Dalal, p. 5

Figure 3

S K F Type R2 Bearing Test Machine



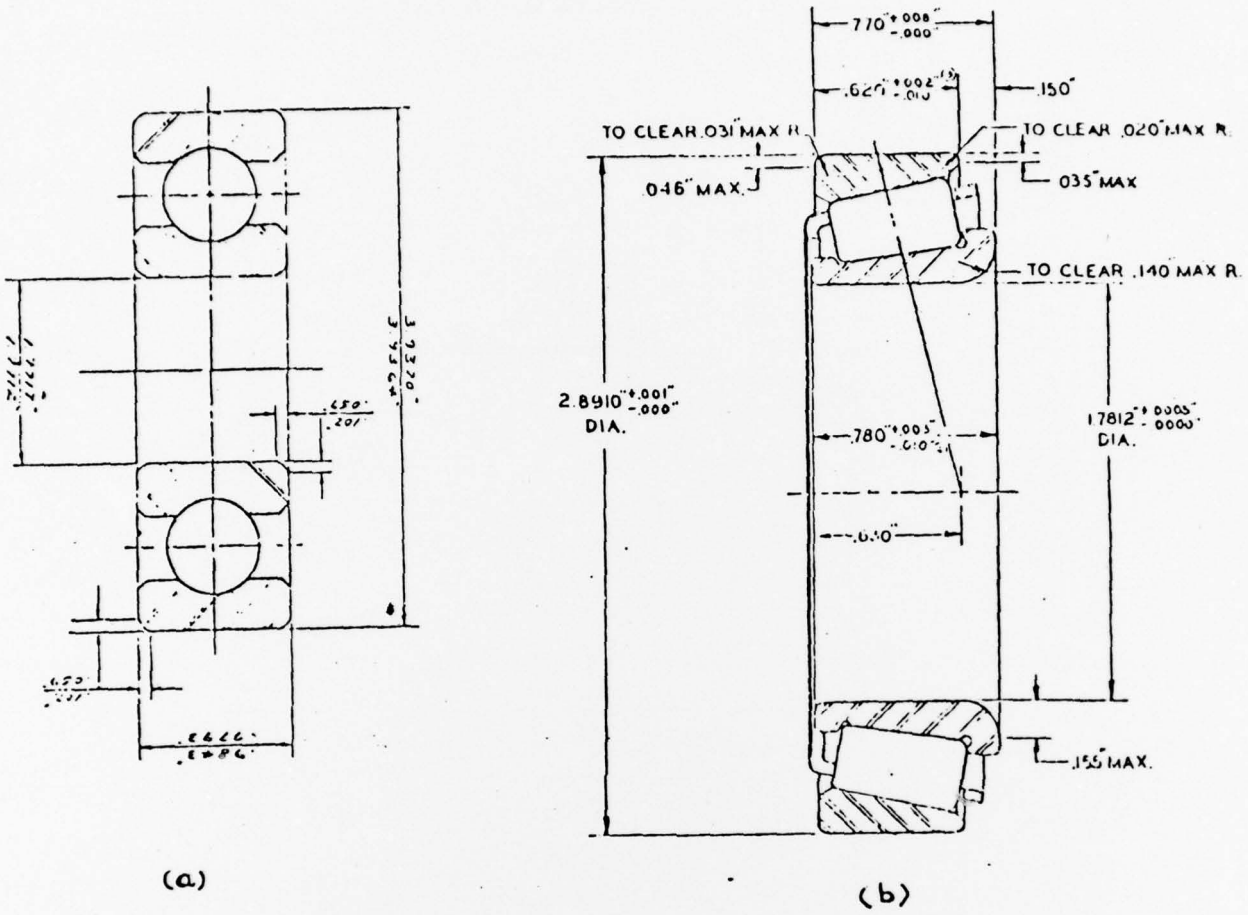


Figure 2. Schematic drawings of test bearings
(a) type 6309 deep-groove ball bearing
(b) LM102949/LM102910 tapered roller bearing

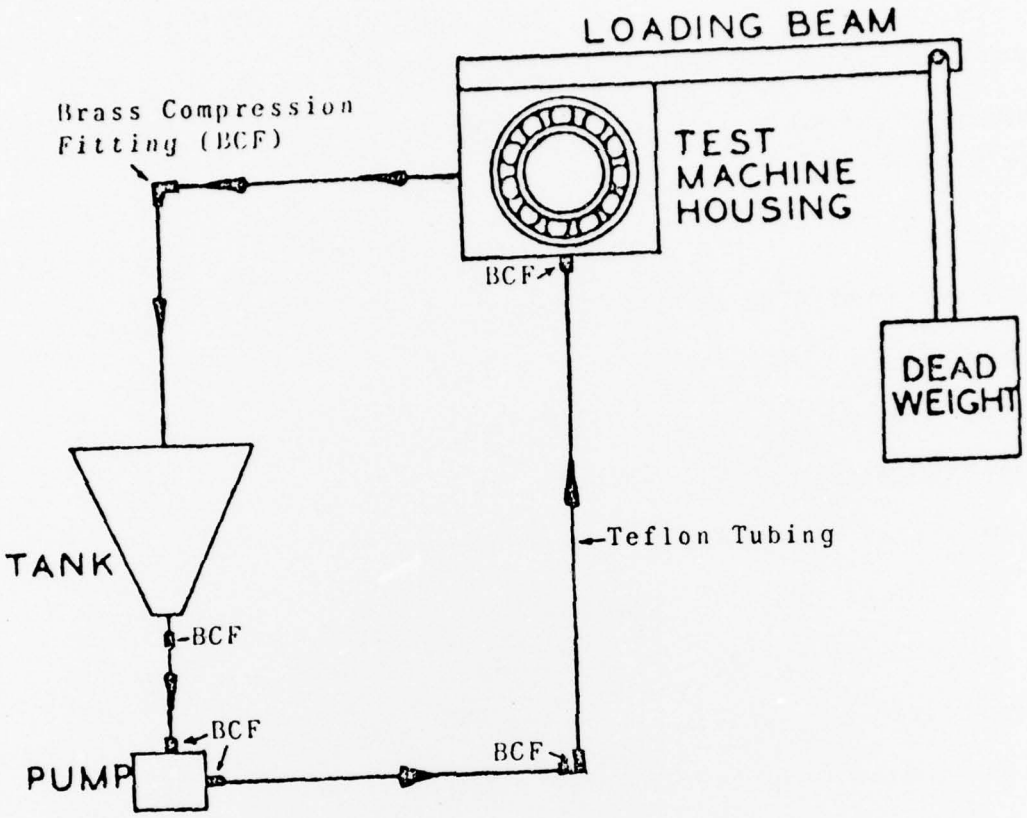


Figure 4. Schematic diagram of closed loop lubrication system for oil analysis program

TABLE 1: Bearing Test Parameters

	6309 Deep-Groove Ball Bearing	LM102949/LM102910 Tapered-Roller Brg.
1. Bore diameter (D, mm)	45	45.2
2. Speed (N, rpm)	9,700	2,900
3. DN X 10^{-6}	0.44	0.13
4. Lube	MIL-L-23699	MIL-L-23699
5. Lube viscosity at 38/100°C (cs)	25/5.1	25/5.1
6. Radial load (kN)	18.8	19
7. Axial load (kN)	0	5.7
8. Bearing capacity (kN)	40.5	46
9. Theoretical L_{10} Life:		
10^6 inner ring revolutions	10	10
10^6 stress cycles	50	130
10. Theoretical L_{50} Life:		
10^6 inner ring revolutions	50	50
10^6 stress cycles	250	650
11. Operating temperature (C)	90	65
12. Lube film parameter	1.8	1.1

ROLLER BEARING RY 115

This bearing was run as an endurance test on the standard SKF R-2 machine shown in Illustration 4. A schematic of the roller bearing is shown in Illustration 5. Illustration 6 is a schematic of the closed loop lubrication system used in the test.

The tapered-roller bearing is made of carburizing grade AISI 4118 steel.

The oil in the oil reservoir was pretreated exactly the same as the oil used in the previous ball bearing endurance test. Again the oil is a MIL-L-23699 qualified oil.

Eight oil samples were taken during this endurance test. They were: [15]

Sample #	1	0.3 million revolutions
	2	4.1
	3	15.6
	4	22.9
	5	31.3
	6	45.6
	7	53.7
	8	57.2

At the finish of this test the oil reservoir was drained and the oil stored. The oil sample roller bearing RY 115 is part of the oil drained from the test system at the conclusion of the test.

The roller bearing failure here was spalling of the cone. The cone was initially dented with a Vickers pyramidal indentor using a 10 kg. load. The indentor has an apex angle of 136° giving a diagonal-to-depth ratio of approximately 4.3[16]. The indentation size was determined to be 153 um. However, the spalling failure did not occur at the Vickers indentation.

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15 Dalal, p. 73.

16 Ibid, p. 5

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DISTRIBUTION LIST

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Department of Fluids & Lubrication
Technology
8500 Culebra Road
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Mechanical Technology Inc.
R&D Division
968 Albany - Shaker Road
Latham, NY 12110
Dr. Peter W. Curwen 1

Midwest Research Institute
425 Volker Blvd.
Kansas City, MO 64110
Mr. Vern Hopkins 1

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Physical Laboratories
1835 Dueber Ave., SW
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C. Pan 1

Massachusetts Institute of Technology
Dept. of Mechanical Engineering
Cambridge, MA 02139
Dr. N. Suh 1

Michigan Technological University
Mechanical Engineering Department
Houghton, MI 49931
Dr. J. Johnson 1

Oklahoma State University
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Defense Advanced Research Project Agency
1400 Wilson Boulevard
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Dr. E. Van Reuth 2

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Imperial College of Sciences & Technology
Department of Mechanical Engineering
Exhibition Road
London SW7 2BX
Dr. P. MacPherson 1

National Bureau of Standards
Metallurgy Division
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Dr. A. W. Ruff 1

Paisley College of Technology
High Street
Paisley, Renfrewshire
Scotland, PA1 2BE
D. Scott 1

University College of Swansea
Department of Mechanical Engineering
Swansea, SA2 8PP Wales
B. J. Roylance 1
M. H. Jones 1

University College of Swansea
Swansea Tribology Center
Swansea, SA2 8PP, Wales
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Creep and Tribology Division
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