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REMOVAL OF WEAR PARTICLES FROM OILS USING HIGH GRADIENT MAGNETIC SEPARATION

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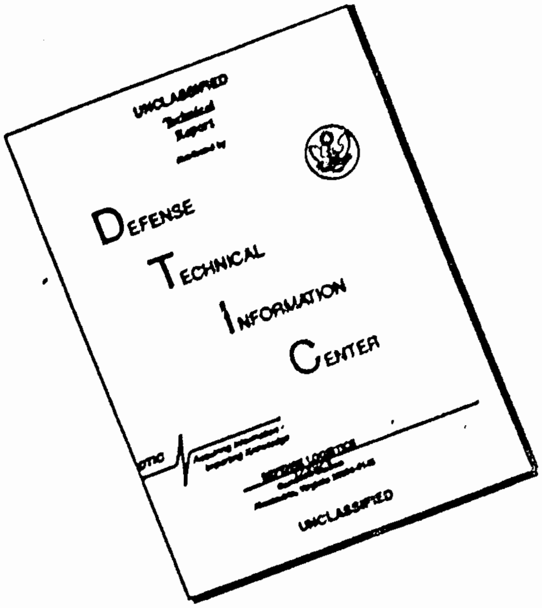

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1.0 INTRODUCTION AND SUMMARY

The principal purpose of the work reported here has been an assessment of the effectiveness with which micron size ferromagnetic wear particles may be removed from lubricating oils by magnetic means. Magnets have been used for many years in the beneficiation of ores, sorting of scrap metal and removal of tramp iron from a wide variety of materials. It is only in recent years, however, that a combination of intense magnetic fields and steep field gradients distributed throughout a large processing volume has been applied to the removal of very small or weakly magnetic particles from materials containing them. It is the application of this technology to the specific task of removing wear particles from lubricating oils that is discussed in this report. A useful review paper covering the general field of magnetic separation with emphasis on high gradient devices was published recently in the IEEE Transactions on Magnetics (Ref. 1).

Although commercial equipment incorporating the high gradient magnetic separation technique is available on the market and is finding applications in mineral processing, ore beneficiation and water purification, the method is still in the development stage. One company manufactures a line of high gradient devices specifically intended for use as filters in lubrication systems, hydraulic systems and in cleaning up cutting oils,[1] but the availability of these items appears to be largely unrecognized, the applications quite limited and performance information

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[1] Frantz Ferro-Filters manufactured by the Frantz Company in Trenton, N.J.

1.0 INTRODUCTION AND SUMMARY (continued)

unavailable. Indeed, there appears to be very little quantitative information to be had regarding the efficiency with which any filter removes wear particles from lubricants, or the consequences of such removal on wear history.

One of the reasons for the general absence of data on the effectiveness of lubricant filtration is the difficulty encountered in making measurements of the quantity and characteristics of wear products in lubricants. For investigations of wear in machines made of ferromagnetic materials, this difficulty has been greatly eased recently by the development during the early 1970's of an instrument, the Ferrograph, designed specifically to provide a means for the extraction, examination and measurement of micron size ferromagnetic wear particles in oils. A description of the Ferrograph is given in Reference 2. This instrument makes possible the preparation of a microscope slide on which the ferromagnetic wear particles contained in a small oil sample are deposited with the larger particles at one end of the slide and continuous size gradation towards finest particles at the other end. Slides prepared in this way may then be examined microscopically for identification of wear particle type - controlled heating of the slide causes different materials to assume different colors - and measurements made of the amount of material present by the area covered.

The work reported here represents an effort to provide quantitative

1.0 INTRODUCTION AND SUMMARY (continued)

information concerning the efficiency with which small ferromagnetic wear particles may be removed from lubricating oils by high gradient magnetic separation, and to determine the dependence of that efficiency upon system parameters such as magnetic field strength and flow rate. An attempt has also been made to provide evidence that lubricant properties are improved by high gradient magnetic filtering in accelerated wear situations. Although the results of such tests have been positive, they must be considered tentative until more comprehensive tests under normal wear conditions have been carried out. Tests of this kind involving normal wear in a Diesel engine are now being planned.

Quantitative determinations of the efficiency of high gradient magnetic filtering of oil were made using clean oil that had been seeded with micron size iron spheres. These determinations were later repeated and fortified by experiments in which oil was circulated through a loop containing both a filter and a wear particle generator in the form of a Falex lubricant test machine. From such work it was learned that a high gradient magnetic filter of a size comparable to oil filters used in cars and trucks operating at a flow rate of one to three gallons per minute and a magnetic field strength between one and two kilogauss is capable of removing virtually all of the ferromagnetic wear particles in the oil leaving only a small residue of very fine submicron particles in the filtrate. Such a filter presents a low impedance to oil flow and has a large trapping capacity in relation

1.0 INTRODUCTION AND SUMMARY (continued)

to the rate of wear particle generation that might be anticipated in a normally operating engine.

Acting on this knowledge, a design, believed to constitute an invention, has been prepared in which permanent magnets are used in an extremely flexible arrangement to accommodate a wide range of flow rates, trapping capacities and field strength requirements. With the high efficiency of ferromagnetic particle removal established and a design in hand that is widely adaptable to particular filtration situations, it remains to identify appropriate applications testing opportunities where filters of this kind can be evaluated quantitatively for wear rate improvement or other useful consequences. Diesel engine tests now being planned are to be carried out in an existing facility at the Michigan Technological University in Houghton, Michigan. Other opportunities of this kind should be sought to carry out evaluations of other potential applications in existing facilities where the tests can be supervised by people with expert knowledge of the application under consideration.

The following sections of this report present: a brief discussion of the high gradient magnetic separation principle; descriptions of the test equipment and procedures used to determine separation efficiency; and, descriptions of the results obtained, including curves of performance characteristics and photomicrographs of Ferrograph slides.

2.0 HIGH GRADIENT MAGNETIC SEPARATION

If a bar of ferromagnetic material is placed in a magnetic field and oriented with its long dimension parallel to the field direction, a north magnetic pole will appear at one end of the bar and a south pole at the other end; it will have been "magnetized" by the field. If the field is uniform, that is, if the intensity of the field is the same everywhere in the neighborhood of the bar, equal but oppositely directed forces will act on the north and south poles. No net force will be present. If the bar is rotated out of alignment with the field direction, these equal and opposite forces will produce a torque tending to realign the bar with the field, but there will be no net force urging the bar to move. If, however, the intensity of the magnetizing field varies from point to point, i.e., if a field gradient is present, the forces acting on the poles will not be equal. A net force will then be present urging the bar to move in the direction of the field gradient. The magnitude of the net force will be proportional to the product of the field intensity and the field gradient. It is this net force, or tractive force as it is called, that is used in magnetic devices designed for sorting materials.

There are three things to note about the magnetic tractive force:

1. A magnetic field must exist to "magnetize" the material being sorted;

2.0 HIGH GRADIENT MAGNETIC SEPARATION (continued)

2. The magnetizing field must be non-uniform; a gradient must be present;

3. The field gradient must be sufficiently steep so that a significant difference in intensity exists over a distance comparable to the dimension of the object upon which the tractive force is expected to act.

It is Item 3 in this list that explains the need for high (steep) gradients in a magnetic sorting device designed to remove wear particles from oil. The "bars" (or particles) in this case have dimensions of the order of 10^{-6} meter; therefore, the field gradients must be sufficiently steep to provide sensible differences in field intensity over a comparable distance. It is, in general, possible to produce such steep gradients only in the immediate vicinity of sharp edges or points on magnetized material or near small diameter magnetized wires. In the magnetic filters used in the work reported here, a distribution of steep field gradients throughout a usefully large processing volume is accomplished by filling the volume with magnetic stainless steel wool. The heart of the filter is a container filled with steel wool to a density of about 5% on a volume basis. When such a container is placed in a uniform magnetic field, the steel wool becomes magnetized thereby producing steep field gradients throughout the contained volume. When oil containing wear particles is caused to flow through such a structure, the particles are also magnetized

2.0 HIGH GRADIENT MAGNETIC SEPARATION (continued)

by the field and trapped by the steep gradients surrounding the steel wool fibers[1].

The elementary physics of magnetic separation is expressed by the following equation for the tractive force,

$$F_m = MV \text{ grad } H \tag{2-1}$$

where

F_m is the tractive force,

M is the magnetization of the particle (magnetic moment per unit volume),

V is the volume of the particle,

grad H is the field gradient,

and the following equation for the hydrodynamic drag which also acts on the particle by virtue of the motion and viscosity of the fluid in which the particle is immersed,

$$F_c = 3\pi\eta bv \tag{2-2}$$

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[1] Although the preceding discussion has been directed at separation of ferromagnetic particles from whatever material they happen to be immersed in, exactly the same considerations apply to sorting of weakly magnetic materials, and even paramagnetic materials, according to susceptibility differences. Stronger fields and steeper gradients are required in such cases.

2.0 HIGH GRADIENT MAGNETIC SEPARATION (continued)

where

η is the viscosity of the fluid,

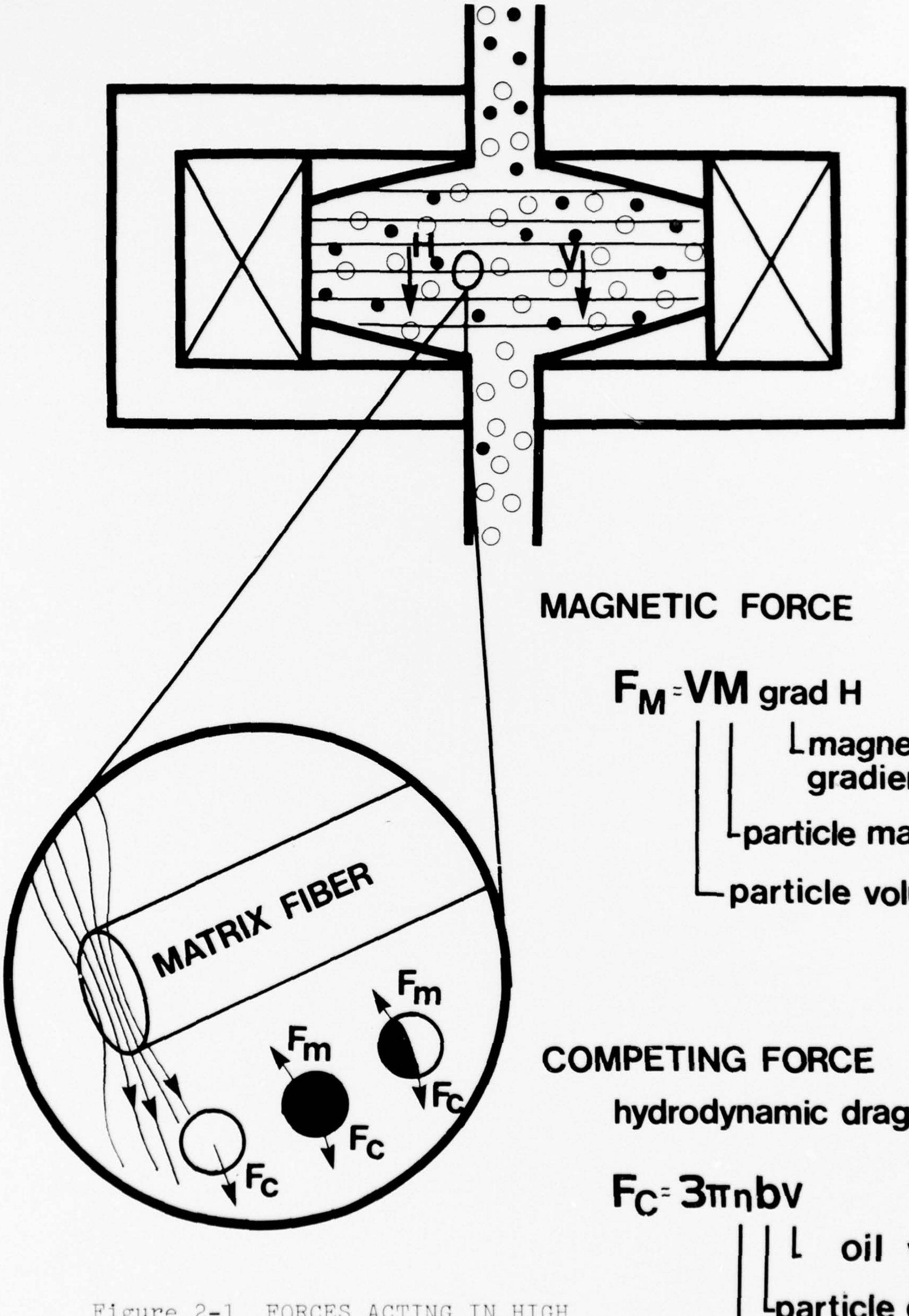
b is the diameter of the particle (assumed spherical)

v is the velocity of the fluid.

For trapping of the particle to occur, it is necessary that F_m be greater than F_c, or

$$MV \text{ grad } H > 3\pi\eta bv \tag{2-3}$$

as illustrated diagrammatically in Figure 2-1.



MAGNETIC FORCE

$F_M = VM \text{ grad } H$

- magnetic field gradient
- particle magnetization
- particle volume

COMPETING FORCE

hydrodynamic drag

$F_C = 3\pi\eta bv$

- oil velocity
- particle diameter
- oil viscosity

Figure 2-1 FORCES ACTING IN HIGH GRADIENT MAGNETIC SEPARATION

3.0 PROCEDURES AND EQUIPMENT

3.1 Oil Samples

During the early stages of the investigation, experiments were conducted with used oil collected at Naval air stations from jet engines and aircraft hydraulic systems. (Oil from helicopter gear boxes was also examined in a parallel program.) This procedure proved to be unsatisfactory because of the time required to get the oil and because the samples, once received, were awkward to deal with. The jet engine and helicopter gear box oils were heavily contaminated with wear polymer, carbon and larger-than-normal wear particles from failed components. The hydraulic oil was so clean that an insufficient quantity of wear material was contained in a volume of reasonable size for analysis. It was concluded from these early tests that useful progress could be made much more quickly and easily with clean oil samples deliberately contaminated by seeding with micron size iron particles. Satisfactory experimental oil samples were prepared with unused Mobil Jet II synthetic oil (MIL-L-23699) seeded with small iron spheres, formed by the carbonyl process[1], ranging in diameter from a fraction of a micron to about three microns. Enough iron was added in powder form to produce samples with concentrations ranging between 100 and 200 parts per million by weight. Later in the program, oil samples were contaminated with real wear particles generated by a Falex Lubricant Test machine (see Appendix I).

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[1] The carbonyl iron powder was obtained from the GAF Corporation in New York

3.0 PROCEDURES AND EQUIPMENT (continued)

3.2 Test Equipment and Procedure

A diagram of the test facility assembled for the purposes of this investigation is presented in Figure 3-1. The facility consists of a holding tank for the oil sample, a variable speed, positive displacement pump, a small solenoidal electromagnet, a canister inserted in the magnet bore containing a high gradient matrix of coarse steel wool, pressure gauges for determining the pressure drop across the matrix, miscellaneous plumbing and a thermostatically controlled heater for warming the oil. The magnet is powered by a 1000 watt, Hewlitt-Packard power supply equipped with controls for independent variation of voltage and current. It is water cooled with a magnetic field strength that can be varied between 0 and 2 kilogauss by appropriate adjustment of the power supply. The canister containing the high gradient matrix is made of 1.5 inch I.D. stainless steel tubing (non-magnetic). Inserted into each end of the canister tube are 4 inch long magnetic stainless steel pole pieces axially bored to provide oil passages. The remaining 6 inch length of canister volume is filled with coarse, magnetic stainless steel wool to a density of 5% on a volume basis. Preliminary tests had shown that the coarse steel wool is to be preferred over finer grades of steel wool and a variety of expanded metal patterns that were also tried. The coarse steel wool combines low impedance to flow with high wear particle capture.

3.2 Test Equipment and Procedure (continued)

In a typical test sequence a sample of seeded oil (1 to 2 gallons) is poured into the holding tank and pumped through the system for about 5 minutes with the magnet off to mix the sample thoroughly. A 3 ounce sample is removed from the mixed oil and set aside for later examination. The magnet is then turned on, the system allowed to run for another 5 minutes and a second 3 ounce sample taken. The parameter under investigation is then varied for as many data points as might be required to produce a curve exhibiting the parametric relationship involved. Analysis of the "before" and "after" samples accumulated in this way is discussed in the next section.

In the tests conducted with seeded oil, the flow velocity through the filter matrix was maintained close to 17 cm per second. This amounts to a bulk flow of about 244 gallons per square foot per minute. Most of the tests were conducted with the oil at ambient temperature near 25°C, the exception being the determination of filtering efficiency as a function of temperature. The hydrodynamic drag forces tending to prevent capture of wear particles in the matrix is proportional to the product of flow velocity and oil viscosity (see Section 2). Since the viscosity of oil decreases markedly with rising temperature, the results of the tests are conservative for applications in which the oil being filtered is hot. This matter is discussed further in Section 4.

Some of the data presented in Section 4 were taken at field intensities greater than the 2 kilogauss maximum field attainable with the equipment described here. This data comes from early experiments with a more powerful magnet. It was subsequently decided to limit the field intensity to the 0 - 2 kilogauss range because little gain in efficiency of filtering was observed at the higher fields and because fields in the lower range can be achieved with permanent magnets. Permanent magnet devices, which require no source of power, are much more attractive for use in vehicles than are the electromagnets that would be required for operation at the higher field levels.

Data for the parametric curves presented in Section 4 were obtained from tests with oil that had been seeded with carbonyl iron powder. Later tests were made with real wear particles generated by a Falex lubricant test machine introduced into the circulating oil loop just after the magnet. The Falex machine, which is described in Appendix I, is a standard test apparatus that causes a steel cylinder to rotate between two V-blocks loaded with a measured amount of force, thereby producing rubbing wear similar to that encountered in journal bearings. In normal test use, the rotating cylinder and V-blocks are immersed in the oil under test, and the effectiveness of lubrication is measured by the amount of wear produced after a given amount of time at a given load, all in accordance with a standard test procedure. In the tests being reported here, the stream of oil flowing through the magnet test loop was directed at the rotating test cylinder just after passing through

3.2 Test Equipment and Procedure (continued)

the magnet; thence it was returned to the pump and circulated again through the magnet and onto the rotating cylinder. In a typical test sequence, clean oil was introduced into the system and circulated around the loop for 5 minutes with neither the magnet nor the Falex machine operating. A sample was then taken and the Falex machine turned on. The Falex machine was allowed to run for a half-hour introducing wear particles into the circulating oil with the magnet remaining off. A second oil sample was then taken and the magnet turned on at some predetermined field level. After 5 minutes of operation with both the Falex machine and the magnet operating, a third sample was taken and the Falex machine turned off leaving the magnet on for an additional 5 minutes, whence a fourth oil sample was taken. The test was then complete.

Tests were also conducted in which the electromagnet was replaced by a permanent magnet solenoid similar in size and shape to the electromagnet but somewhat smaller. The central field in the bore of the permanent magnet with the filter canister removed is 0.8 kilogauss. These tests were conducted to demonstrate that effective removal of wear particles from oil is indeed feasible with equipment of reasonable size.

A photograph of the test equipment showing the electromagnet and its power supply, the Falex wear particle generator, the pump and interconnecting plumbing is presented in Figure 3-2. The filter canister

3.2 Test Equipment and Procedure (continued)

containing the steel wool matrix is seen installed in the electromagnet in Figure 3-2 and disassembled in Figure 3-3. Also seen in Figure 3-3 is the permanent magnet used in the tests.

3.3 Analysis

The samples taken during the test sequences described in the foregoing section were analyzed with the aid of a Ferrograph (Ref. 2), an instrument designed to precipitate magnetic particles contained in a fluid onto a microscope slide for examination under high magnification. Particles in the size regime of interest in this study are effectively colloidal in the sense that they will remain suspended in oil indefinitely unless they are acted upon by a force sufficiently strong to pull them out. The Ferrograph precipitates those particles in the oil that are magnetic, or that contain magnetic inclusion, by flowing the oil sample along a microscope slide positioned above a long, narrow gap in a cylindrical magnet. The slide is supported at one end by a small shelf above the magnet while the other end rests on the magnet surface. A small peristaltic pump removes oil from a sample bottle and deposits it on the microscope slide near the end supported by the shelf. As the oil flows along the slide, the particles contained in it find themselves in a magnetic field that increases in both intensity and steepness of gradient as a function of distance along the slide. Consequently, tractive forces act on the magnetic particles in the oil causing the larger ones to precipitate first as the oil moves down

3.3 Analysis (continued)

the slide toward the other end. After the oil sample has been run through the system for a sufficient length of time (usually about 5 minutes), a fixative liquid is caused to flow along the slide. This liquid removes the remaining oil and, upon evaporation, causes the precipitated particles to adhere to the slide so that it can be removed from the magnet without upsetting the particle distribution. The finished slide, called a ferrogram, is then ready for microscopic examination.

The heart of the Ferrograph showing the magnet with a microscope slide positioned above it is shown in Figure 3-4 together with a photograph of a typical ferrogram.

Examination, measurement and recording of the particle distributions captured on ferrograms is accomplished with a Ferroscope, a high quality microscope equipped with accessory devices for making photomicrographs and photoelectric measurements of transmittance or reflectance at selected positions along a ferrogram. The assessments of filtration efficiency presented in Section 4 have been made both photoelectrically and with the aid of photomicrographs. The photoelectric measurements yield data in the form of numbers which can be plotted as graphs, but in doing so significant information concerning the kinds of particles in the field of view is lost. This is particularly important when measurements are made under conditions of high filtration efficiency when most or all of the ferromagnetic particles have been

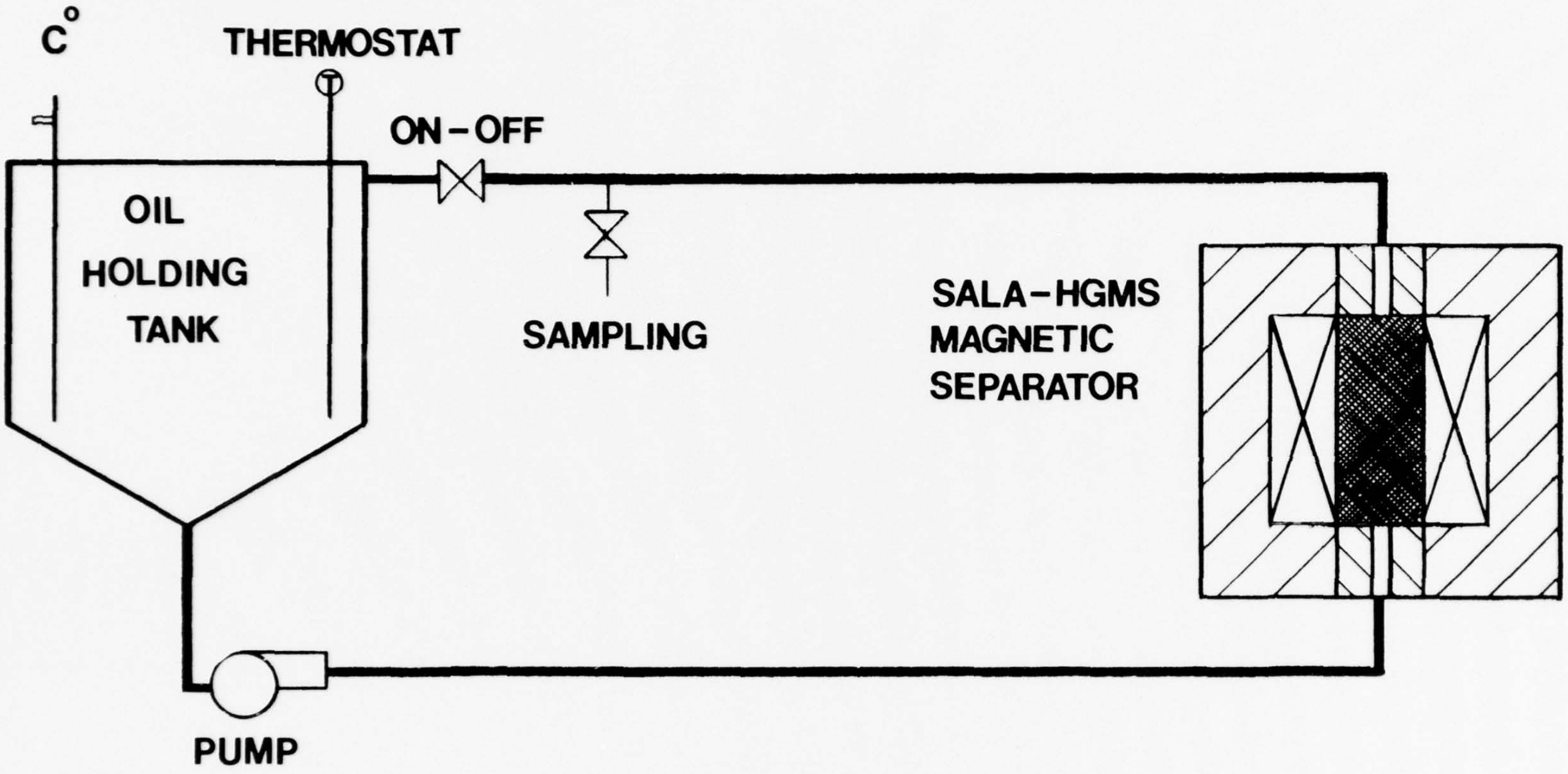
3.3 Analysis (continued)

removed. The photoelectric measurement is then dominated by the presence of other debris always present in the field of view, whereas visual examination of a photomicrograph of the same field provides easy discrimination between the wear particles and whatever else may be there. Thus, a photoelectric measurement might indicate 95% efficiency of filtration in a situation where visual examination would show that 99.99% of the particles of interest had been removed. For this reason, the graphs presented in Section 4 showing dependence of filtration efficiency on system parameters are to be considered conservative in their indications of maximum efficiency.

The heaviest deposit on a ferrogram generally occurs at the point where the liquid flows onto the slide. The accumulation at this point is called the "entry deposit" and consists of a mixture of particles of all sizes. The entry deposit from an oil sample with a high concentration of wear particles (50 to 100 parts per million by weight) can be many particles thick. It was determined during the course of this investigation that the volume of the entry deposit is a usefully reliable and reproducible measure of the relative concentration of particles in successive samples of oil. The entry deposit volume is measured by determining the percent of the area covered by particles within the field of view of the microscope at a magnification of 100X and the thickness of the deposit by focal adjustment at 1000X. The percent of the area covered by particles was determined from reflectivity measurements with the photoelectric attachment. In most cases the measured

3.3 Analysis (continued)

deposits were only one particle layer thick and, therefore, required only measurements of area covered for comparison purposes. The data for the graphs presented in Section 4 was obtained in this way from tests with oil that had been seeded with carbonyl iron powder. The photomicrographs, also presented in Section 4, were all made in the region of maximum particle density of the entry deposits formed on the various ferrograms used.



CLOSED LOOP MULTIPLE PASS
PUMPED FILTRATION SYSTEM

FIG 3-1

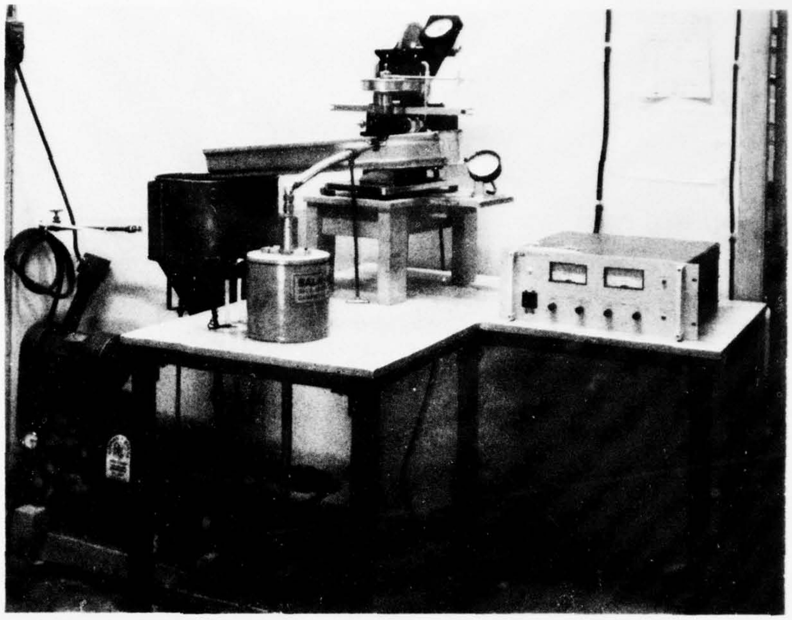


Fig. 3-2 Test facility showing pump, electromagnet, Falex machine, oil reservoir above pump and magnet power supply. Canister containing steel wool matrix is installed in magnet.

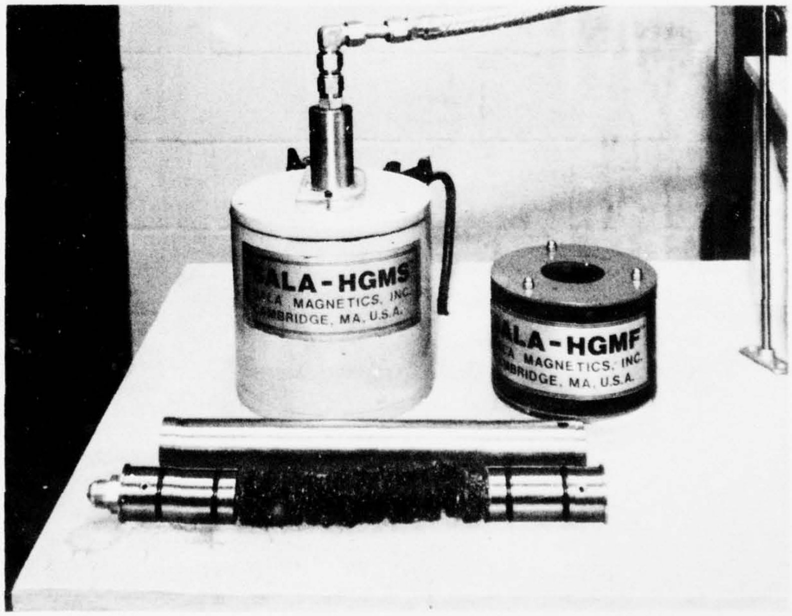
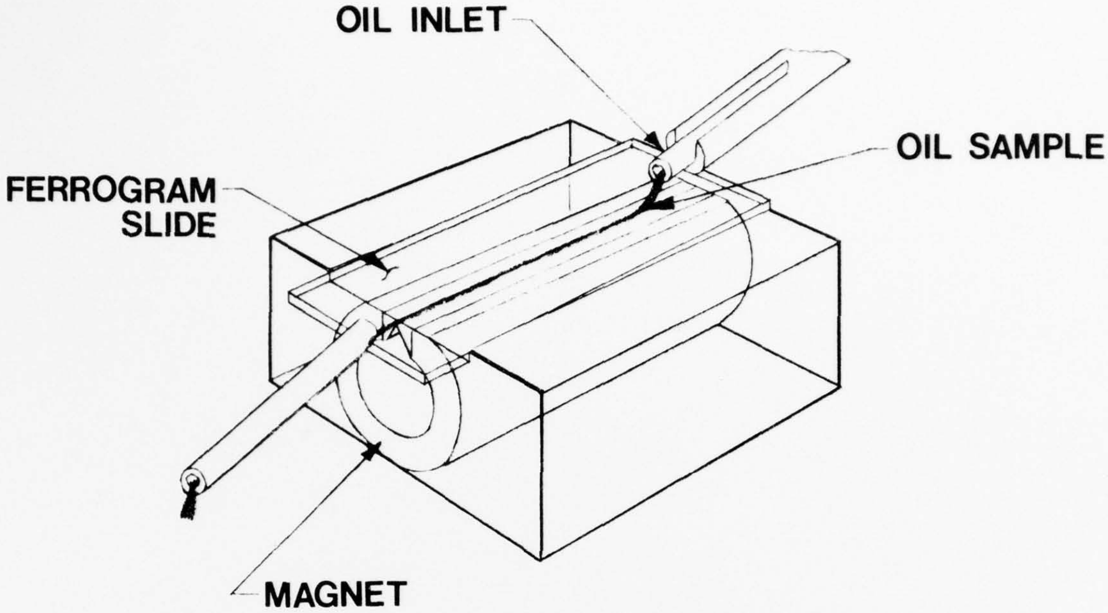
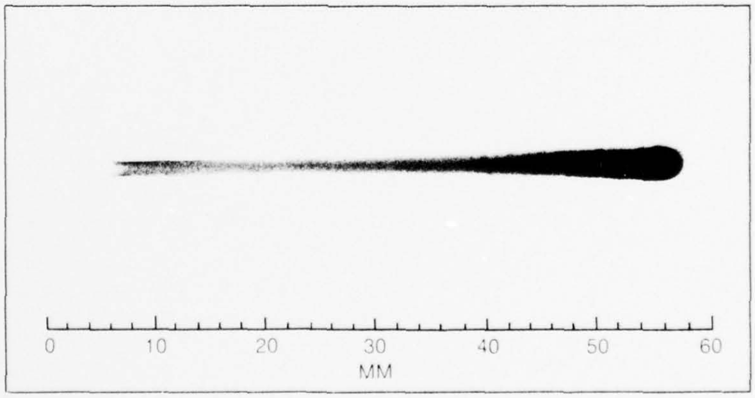


Fig. 3-3 Electromagnet with canister in place, permanent magnet and disassembled canister showing matrix material. The canister tube is 14 inches long.





FERROGRAM

FERROGRAPHIC METHOD OF ANALYSIS

FIG. 3-4

4.0 TEST RESULTS

4.1 Visual Assessments - Seeded Oil

Figures 4-1 through 4-5 are photomicrographs made at high magnification (1000X) of the entry deposit region in ferrograms prepared during a sequence of test runs in which the parameter being varied was magnetic field intensity. The test involved circulating 4 gallons of oil seeded with 100 parts per million by weight of carbonyl iron spheres through the magnetic filter at a filter flow velocity of 17 cm per second. The oil was at ambient temperature, approximately 25°C.

Figure 4-1 is a photomicrograph of a ferrogram made from an oil sample taken while the oil was circulating through the system before the magnet was turned on. The scale of the photomicrograph is 1 micron = 1 millimeter. The tiny iron spheres can be seen to range in size from a maximum of 3 microns in diameter down to less than a micron. Only one layer of a quite thick entry deposit is seen here because of the small depth of field of the microscope at such high magnification. The deposit was actually about 40 microns thick.

Figure 4-2 was made from an oil sample taken after the magnet had been operating for 5 minutes at a field strength of 0.5 kilogauss. The entry deposit is seen to be greatly reduced. The chains of particles seen there are only one particle thick with large spaces between them. (The chains form along the field lines of the Ferrograph magnet.)

Figure 4-3, made from a sample taken after 5 minutes of operation at a

4.1 Visual Assessments - Seeded Oil (continued)

field of 1 kilogauss, shows still fewer particles with a noticeably smaller average size.

Figure 4-4 was made from a sample taken at 1.5 kilogauss. Particle removal is seen to be essentially complete; only one chain, consisting of 2 particles, is left. Figure 4-5, made from a sample taken after operation at 2 kilogauss for an additional 5 minutes, also shows virtually complete removal of the seeded iron spheres.

The test sequence described in the foregoing paragraphs clearly demonstrates that micron size ferromagnetic particles may be removed with high efficiency from oil flowing through 6 inches of coarse stainless steel wool (packed to a volume density of 5%) at a velocity of 17 cm per second (equivalent to 244 gallons per square foot per minute) and a temperature of 25°C when the steel wool is immersed in a magnetic field with an intensity of 1.5 kilogauss or greater. The oil used in these tests was Mobil Jet II (MIL-L-23699).

4.2 Parametric Tests - Seeded Oil

The efficiency of filtration determined by Ferrographic analysis and presented visually in the foregoing section has been converted into numbers by measurements of the entry deposit volume as described in Section 3.3. These measurements are made with the aid of a photoelectric attachment that uses reflectance as a measure of the fractional area within the microscope field covered by particles precipitated from an oil sample.

4.2 Parametric Tests - Seeded Oil (continued)

A low reflectance measurement corresponds to a large percentage of the area covered by particles. Measurements of this kind, made with the microscope set at a magnification of 100X, were used to determine filtration efficiency versus magnetic field, oil flow rate, oil temperature and matrix loading. The results of the measurements are plotted in Figures 4-6 through 4-9.

Figure 4-6 displays two plots of entry deposit volume (in units of 10^3 micron^3) versus field intensity in kilogauss, one for a flow velocity of 15 cm per second and one for a velocity of 30 cm per second. The curves show better than 90% reduction of entry deposit volume at both flow velocities for fields in excess of about 1 kilogauss.

Figure 4-7 shows the dependence of filtration efficiency on flow velocity for two values of field intensity, 0.54 and 2.0 kilogauss. Here the competition between hydraulic drag forces and tractive magnetic forces is evident at the lower field intensity and is beginning to appear at a 40 cm per second flow velocity for the higher field. It is to be noted that these runs were made at an oil temperature of 25°C, and that the substantially lower oil viscosity at normal engine operating temperatures (see Figure 4-8) would greatly lessen the competing drag forces. Even at 25°C, however, filtration efficiency remains better than 90% at a flow velocity of 40 cm per second (574 gallons per square foot per minute) with a 2 kilogauss field.

4.2 Parametric Tests - Seeded Oil (continued)

Figure 4-8 exhibits explicitly the influence of oil temperature on filtration efficiency at a flow velocity of 17 cm per second and a field intensity of 0.5 kilogauss. The viscosity of the oil as a function of temperature is also shown.

After long periods of operation, or in the presence of heavy particle contamination, the steel wool matrix in the magnetic filter will become loaded with particles, and the efficiency of filtration will begin to diminish. This effect is illustrated in Figure 4-9 where it is seen that filtration efficiency begins to decline at a matrix loading of about 50 grams, which happens to be very close to the weight of the matrix. Since the accumulated particles and the matrix are materials of similar density, this result indicates that filtering efficiency begins to decline when the volume of captured particles is approximately equal to the volume of material in the capturing matrix.

The pressure drop across the filter matrix depends upon the flow velocity, the matrix loading and the viscosity of the oil. Figures 4-10 and 4-11 are plots of the pressure drop as a function of flow velocity and matrix loading, respectively, for the Mobil Jet II oil (MIL-L-23699) used in the tests reported in this section.

4.3 Discussion of Tests with Seeded Oil

It is to be noted that none of the data points used to construct the curves presented in Section 4.2 show filtration efficiencies as great as the efficiency indicated by visual assessment of the photomicrographs presented in Section 4.1. This is due to the unreliability of reflectance measurements for determination of particle concentration at very low concentration levels, as discussed in Section 3.3.

In these seeded oil experiments it has been demonstrated that magnetic filtration can be extremely effective at field levels attainable by permanent magnets if the contaminant is ferromagnetic material in the form of micron size spheres. It is tempting to assume that filtration will be equally effective when the contaminant consists of real wear particles produced by rubbing or rolling contact between parts made of ferromagnetic material. There remains a concern, however, that the differences in particle shape and size distribution that clearly exist between the seeded spheres and real wear particles could lead to differences in filtration effectiveness. It was, therefore, decided that, in the interest of enhancing the credibility of the results, further tests should be conducted with real wear particles present in the oil. Preliminary arrangements were made to carry out such tests at a Naval facility engaged in wear test work, but it was ultimately decided that the tests could be conducted more conveniently at less cost by adding a relatively simple wear particle generator to the test loop used in the seeded oil experiments. This work is described in the next section.

4.4 Tests with Real Wear Particles

A photograph of the laboratory test equipment with a Falex lubricant wear test machine included in the loop to serve as a wear particle generator has been presented in Figure 3-2. The Falex machine is described in Appendix I. A typical test sequence involving the use of the Falex machine was presented in Section 3.2.

Figure 4-12 is a photomicrograph made near the entry deposit region of a ferrogram prepared from oil containing a heavy concentration of wear particles produced by the Falex machine. The magnification is 100X. Figure 4-13 is a photomicrograph of the same region of the ferrogram at a magnification of 1000X.

Figures 4-14 through 4-21 are photomicrographs of the entry deposit regions of ferrograms made during a test sequence run to demonstrate filtration efficiency as a function of magnetic field intensity. All of the photomicrographs in this sequence were made at a magnification of 100X.

The oil used in these tests was Quaker State 10W-30 at room temperature. Since the viscosity of the Quaker State oil at room temperature is about three times that of the Mobil Jet II oil used in seeded tests, the flow velocity was correspondingly reduced to keep the hydrodynamic drag approximately the same as in the seeded oil tests for particles of similar shape and size. The flow through the experimental loop in the real wear particle tests using Quaker State oil was at the rate of

4.4 Tests with Real Wear Particles (continued)

one gallon per minute; a two quart volume of oil was used in all the tests. (The rate of flow in the seeded oil tests was three gallons per minute.)

Figure 4-14 shows the entry deposit region of a ferrogram made with clean oil taken directly from the can. Bits of material of the kind seen there are invariably present in "clean" oil.

Figure 4-15 is the entry deposit region of a ferrogram made from a sample that had been circulating through the system for 5 minutes with both the magnet and the wear particle generator turned off. The aligned particles seen here were left over in the system from a prior test.

Figure 4-16 shows the entry deposit formed from a sample taken after the Falex wear particle generator had been operating for ½ hour with a 650 pound load acting on the Falex V-blocks.

Figure 4-17 is the entry deposit region from a sample taken after 5 minutes of magnet operation at a field intensity of 0.25 kilogauss with the wear particle generator still working.

Figures 4-18, 4-19 and 4-20 show the results of filtering at field intensities of 0.5, 1.0 and 2.0 kilogauss, respectively. The duration of filtering at each of these field levels was 5 minutes, and the wear particle generator continued to operate during these intervals.

4.4 Tests with Real Wear Particles (continued)

Figure 4-21 is the entry deposit region after an additional 5 minutes of operation at a field intensity of 2.0 kilogauss with the wear particle generator turned off.

By visual assessment of the photomicrographic results that have been presented in Figures 4-14 through 4-21 it is clear that the high efficiency of removal of ferromagnetic particles demonstrated by the seeded oil tests holds up very well in the presence of real wear particles. In all of these photomicrographs, the ferromagnetic wear particles are readily identified and distinguished from the other debris present because they are arranged in vertical lines by the magnetic field of the Ferrograph while other material is deposited randomly.

4.5 Permanent Magnet Filter

Although there is no reason to suspect that the filtration efficiency achievable with a permanent magnet filter will differ from that observed with an electromagnetic device operating at the same field intensity, tests were conducted with a readily available permanent magnet simply to demonstrate that it does indeed work. The permanent magnet that was used is solenoidal in shape and slightly smaller than the electromagnet. (See Figure 3-3.) The axial magnetic field intensity in the center of the magnet bore is 0.8 kilogauss. The same canister and matrix were used as in the wear particle tests described in the previous section. The test loop, including the Falex wear particle

4.5 Permanent Magnet Filter (continued)

generator, is operated in the same way as in the prior test, except that the magnet was not installed around the canister until after the Falex machine had been operating for one-half hour to build up a concentration of wear particles in the oil.

Figure 4-22 is a photomicrograph of the ferrogram entry deposit produced from a sample of oil taken after the Falex wear particle generator had been operating for one-half hour without the magnet.

Figure 4-23 shows the entry deposit formed after the magnet had been installed and the loop operated for 5 minutes at a flow rate of one gallon per minute with the Falex machine continuing to run. (The sample consisted of 2 quarts of 10W-30 Quaker State oil.)

Figure 4-24 is the entry deposit seen after 5 more minutes of loop operation with the Falex machine turned off.

4.6 Wear Tests

The ultimate measure of filter effectiveness is the extent to which wear rates are reduced when the filter is included in the lubrication loop. Some preliminary wear tests were made with the Falex lubricant test machine described in Appendix I. The tests were conducted in accordance with the procedure given in the A.S.T.M. standard wear test for fluid lubricants, D-2670-67, which the Falex machine is designed to perform. In this test, wear is measured by the setting of a

4.6 Wear Tests (continued)

micrometer rachet wheel required to reach a given load on the specimen before and after operating the machine for a specified length of time at a specified load. Measurement results are stated in terms of the difference in the rachet wheel tooth number before and after the test. Each tooth represents a combined total wear of the test pin and loaded V-blocks amounting to $10^{-3}/18$ inch. The test results are presented in Table 4-I. Quaker State 10W-30 oil was used in these tests at a field intensity of 2 kilogauss and a flow velocity of 5.7 cm per second at 25°C.

TABLE 4-I

Wear Test Measurements

Test Number	Magnet On (teeth)	Magnet Off (teeth)	Improvement (Off/On)
1	6	4	0.67
2	5	5	1.00
3	4	6	1.50
4	4	6	1.50
5	6	7	1.17
6	2	3	1.50
7	3	9	3.00
8	3	5	1.67

It is to be emphasized that the measurements presented in Table 4-I are preliminary: the scatter suggests that the measurement technique might be improved. The average of these measurements does, however, indicate half again as much wear without the filter as with it.

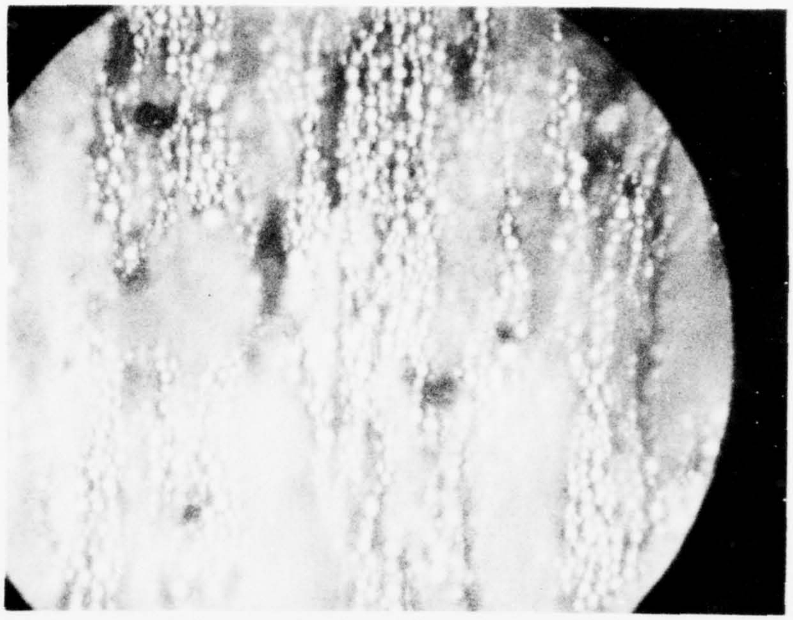


Fig. 4-1 Entry deposit from oil seeded with 100 ppm carbonyl iron spheres. Magnet off. Magnification 1000X.

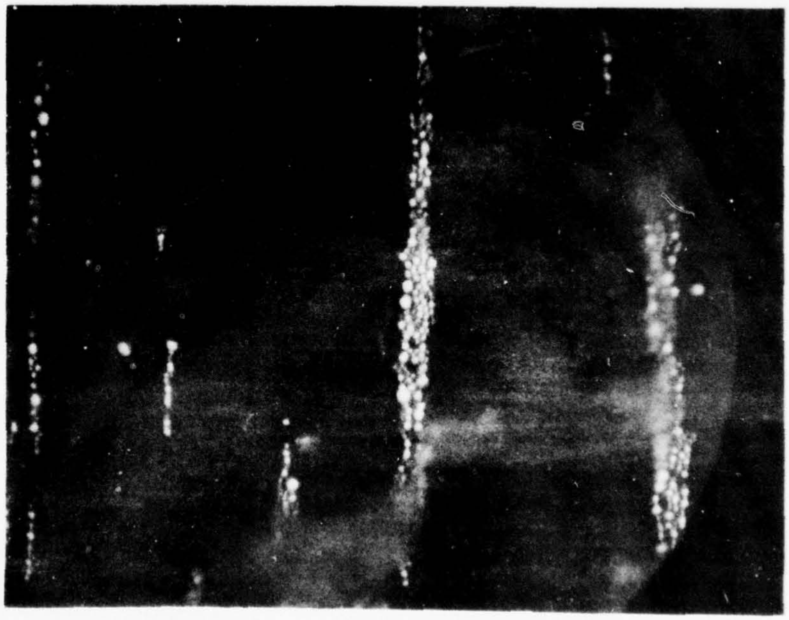


Fig. 4-2 Entry deposit from same oil after 5 minutes of filtering at field intensity of 0.5 kilogauss. Flow velocity 17 cm/sec. Temperature 25°C. Magnification 1000X.

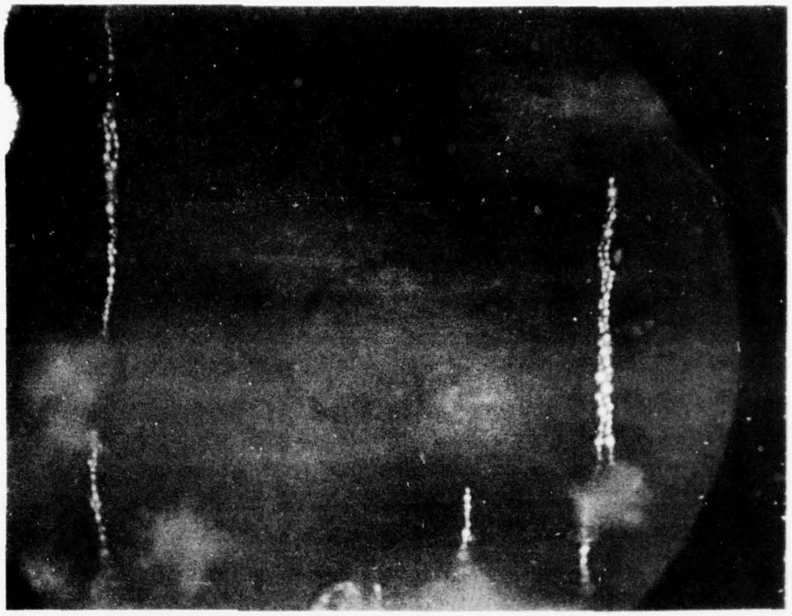


Fig. 4-3 Entry deposit after 5 minutes of additional filtering at field intensity of 1.0 kilogauss. Same oil and conditions as Fig. 4-2. Magnification 1000X

Fig. 4-4 Entry deposit after 5 more minutes of filtering at 1.5 kilogauss. Same oil and conditions as Fig. 4-2. Magnification 1000X.

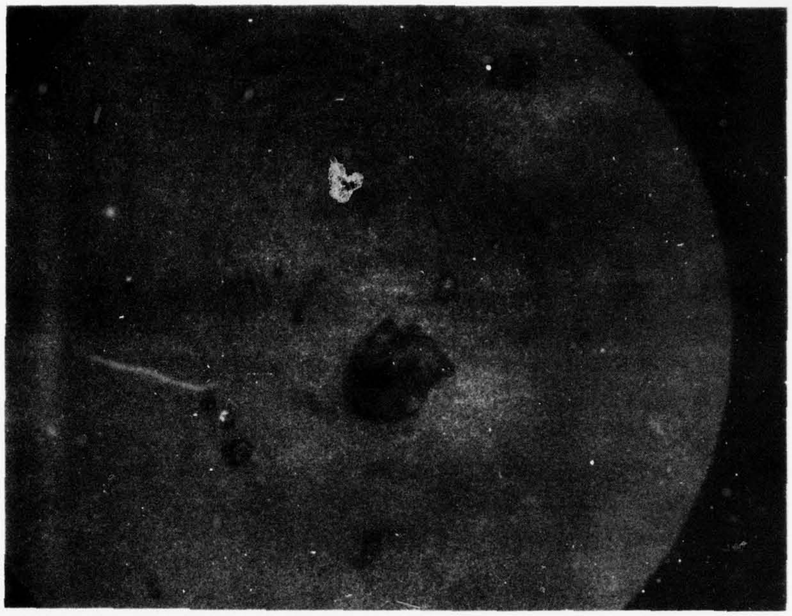
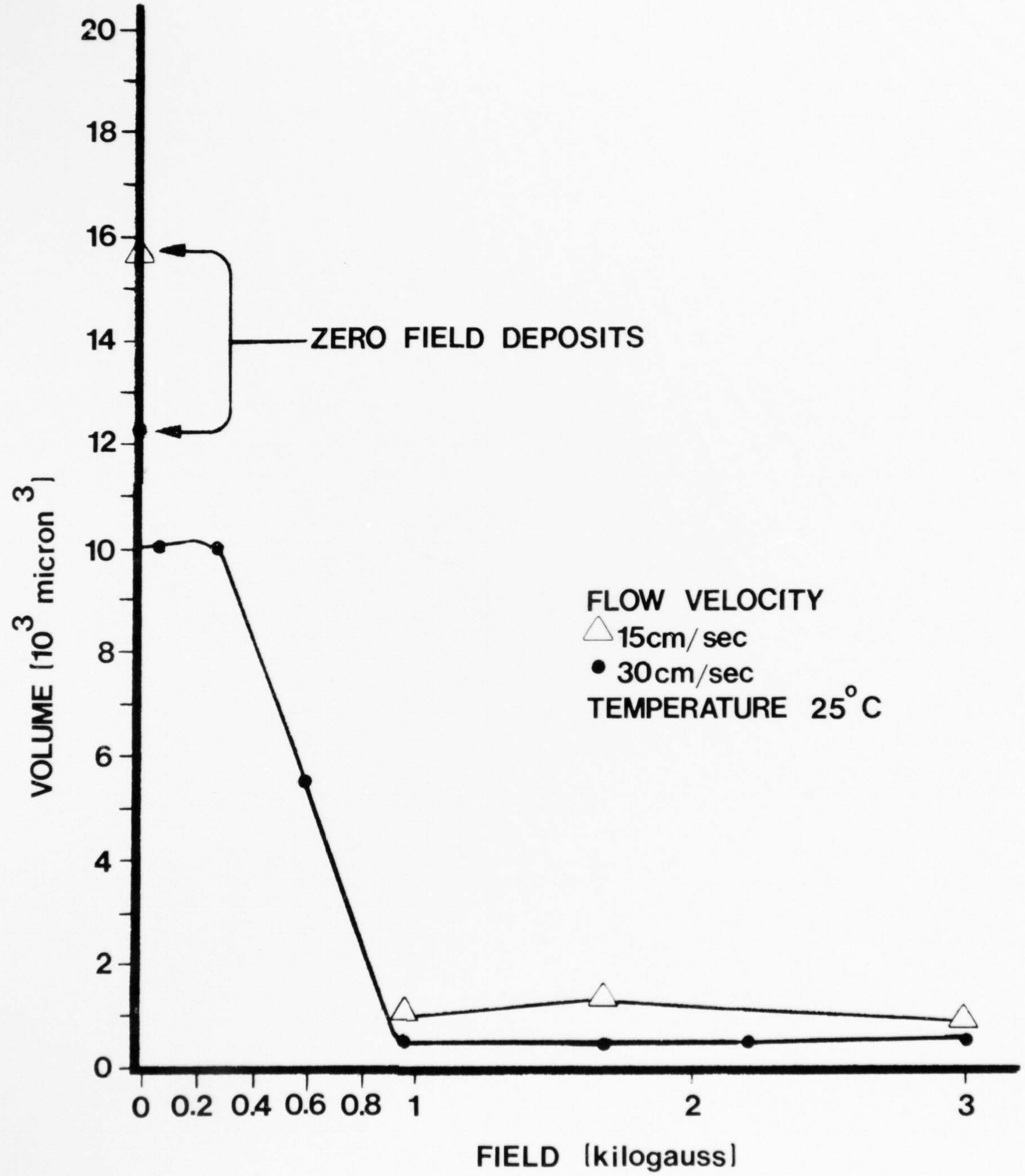


Fig. 4-5 Entry deposit after another 5 minutes of filtering at 2.0 kilogauss. Same conditions as in Fig. 4-2. Magnification 1000X.

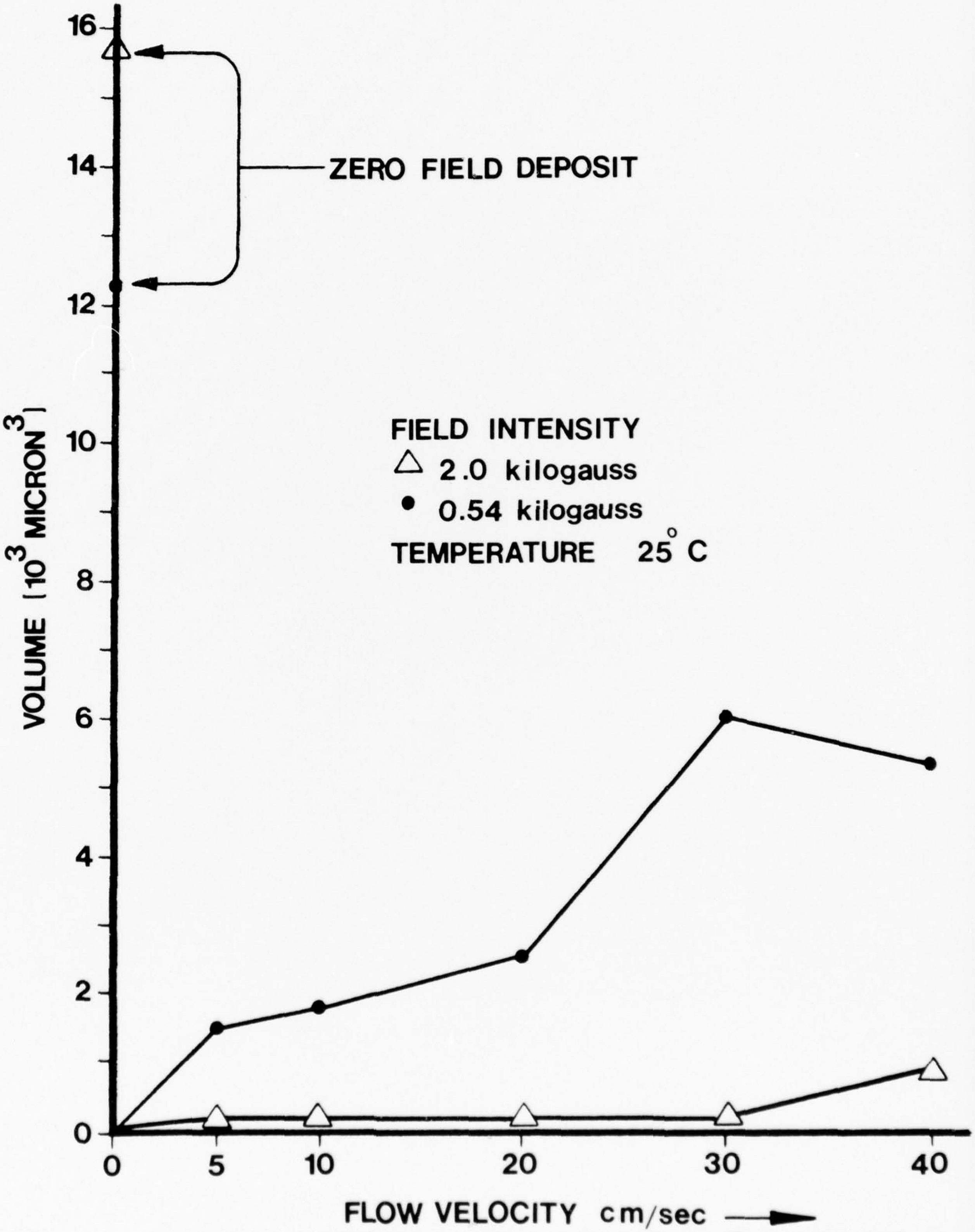
FERROGRAPHIC METHOD OF ANALYSIS

FIG. 3-4



ENTRY DEPOSIT VOLUME
VS. MAGNETIC FIELD
MOBIL II SEEDED

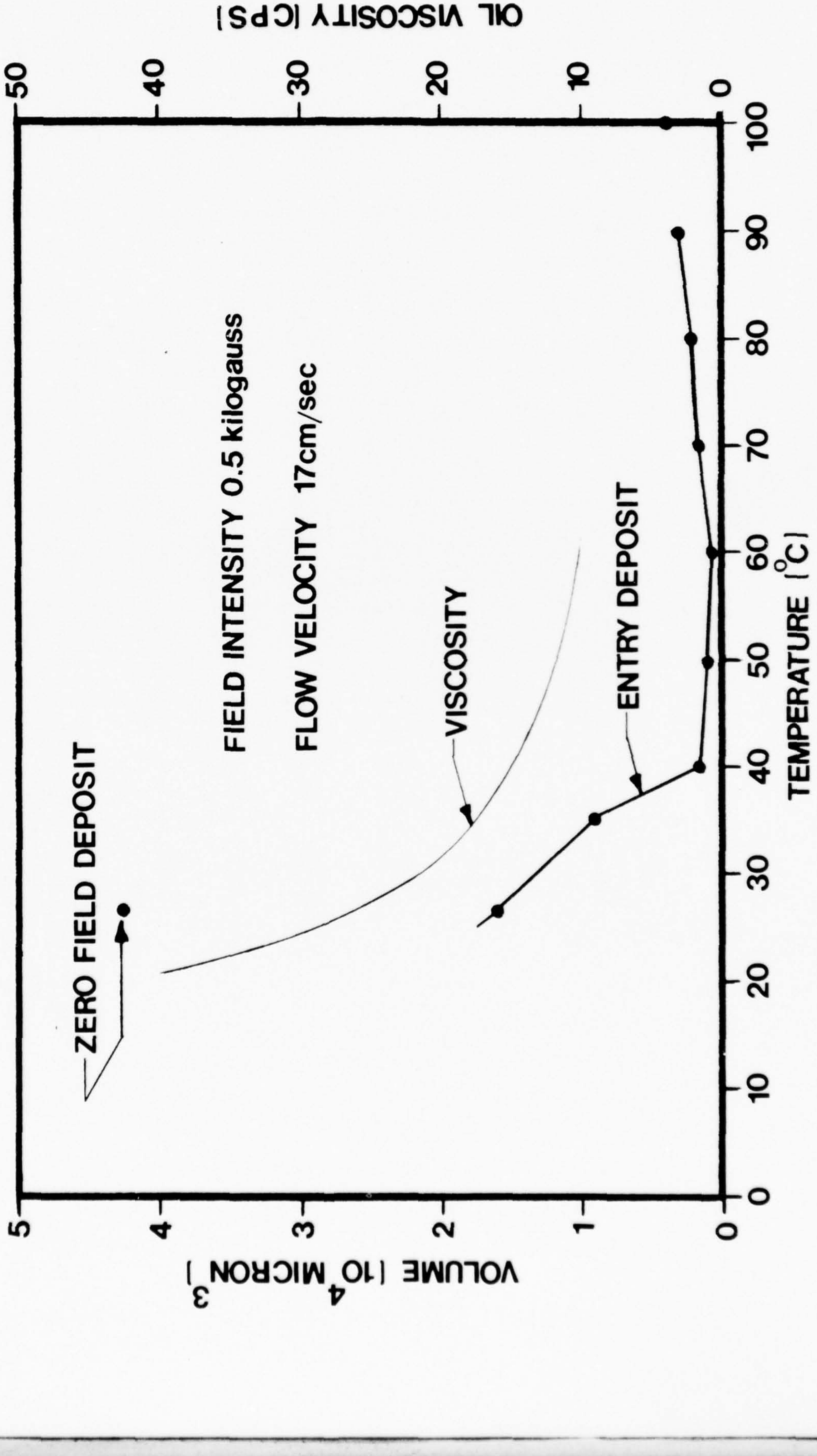
FIG 4-6



ENTRY DEPOSIT VOLUME VS. FLOW VELOCITY

MOBIL II SEEDED

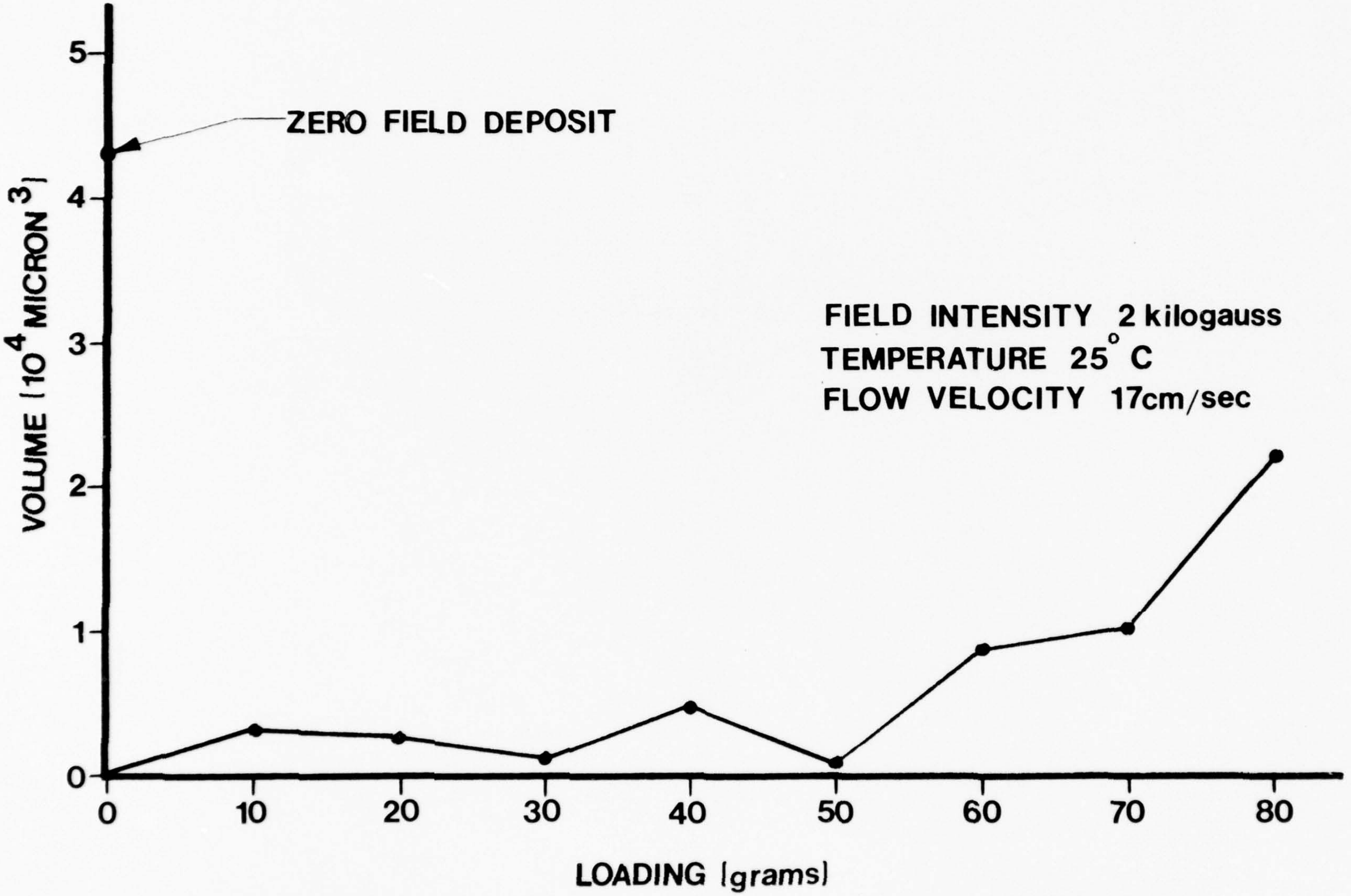
FIG 4-7



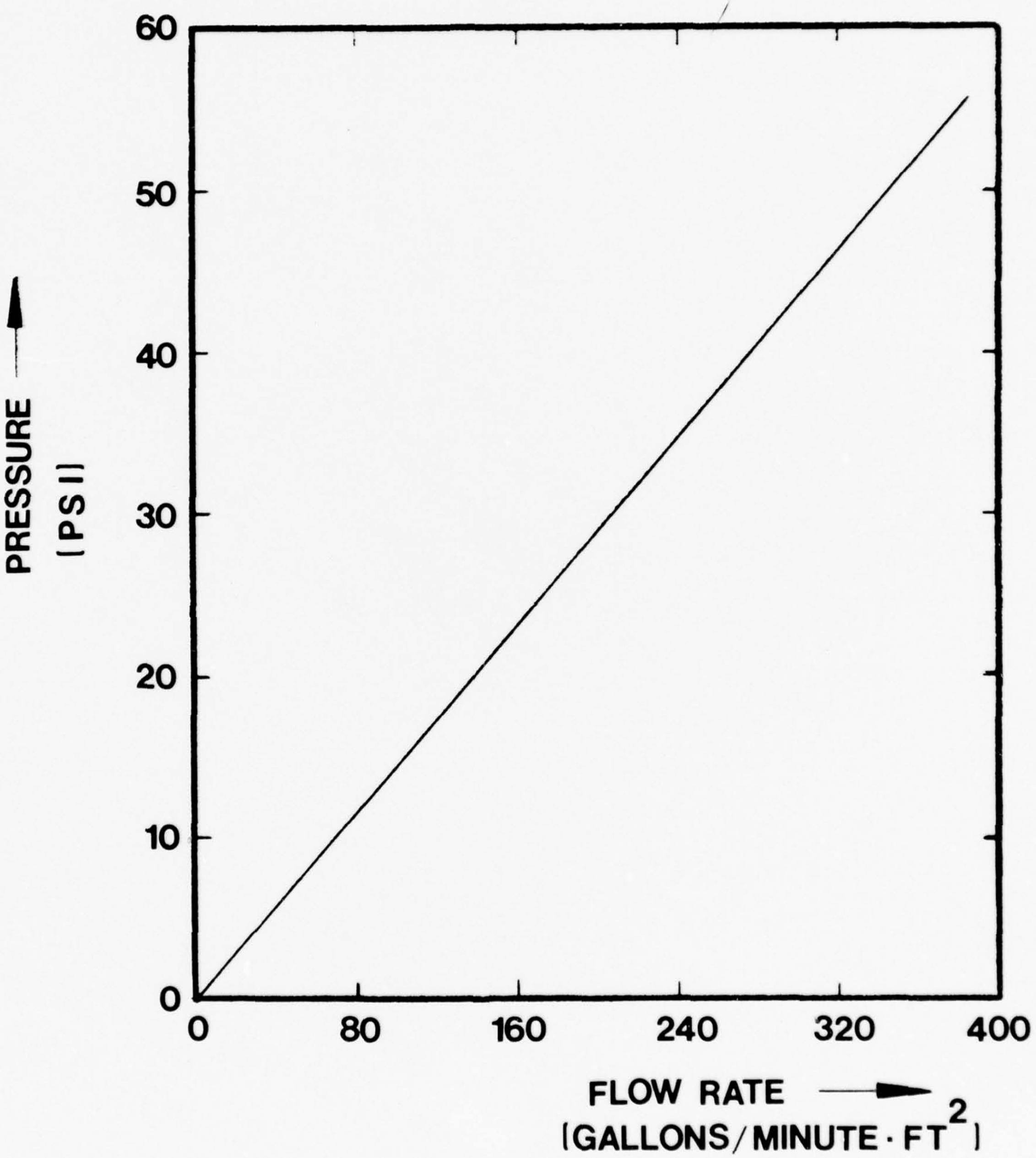
ENTRY DEPOSIT VOLUME AND OIL VISCOSITY VS. OIL TEMPERATURE

MOBIL II SEEDED

FIG 4-8

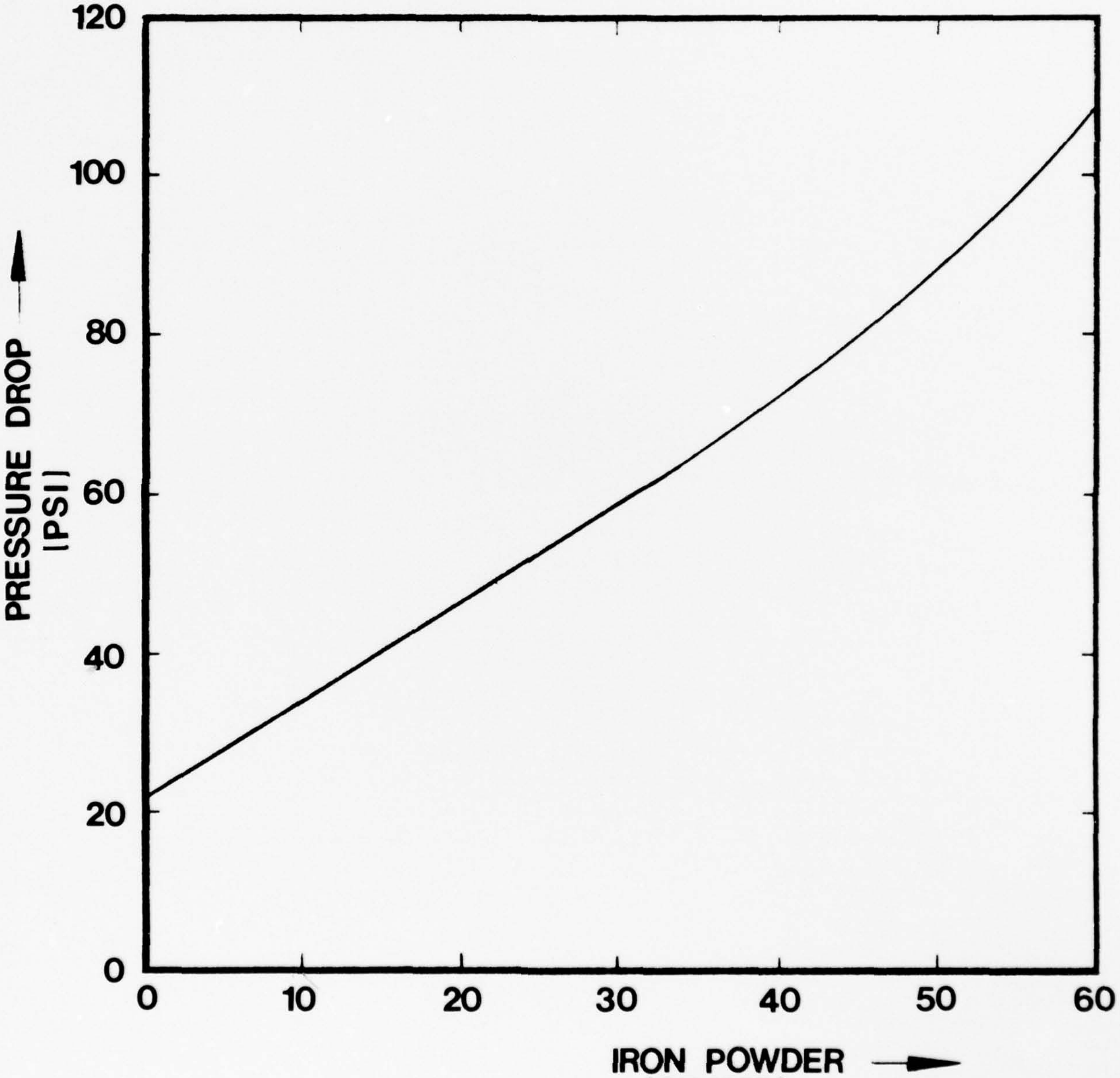


ENTRY DEPOSIT VOLUME VS. MATRIX LOADING
MOBIL II SEEDED
FIG 4-9



PRESSURE DROP VS. FLOW RATE FOR 6 INCH LONG 5% DENSITY COARSE STAINLESS STEEL WOOL MATRIX (~65 GRAM) MOBIL II OIL

FIG 4-10



PRESSURE DROP VS. MATRIX LOADING FOR 65 GRAM, 6 INCH LONG, COARSE STAINLESS STEEL WOOL MATRIX. MOBIL II OIL

FIG 4-11

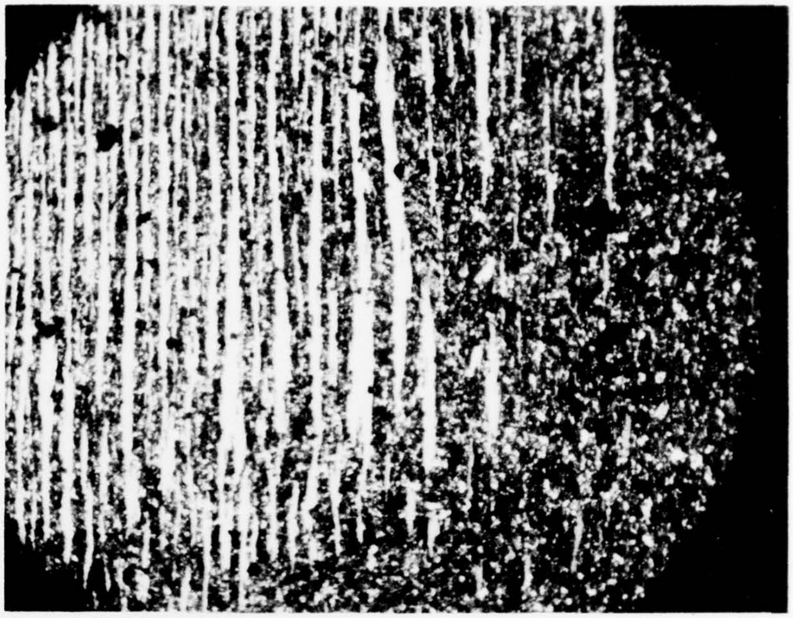


Fig. 4-12 Entry deposit from oil containing heavy concentration of wear particles produced by the Falex machine. Magnification 100X

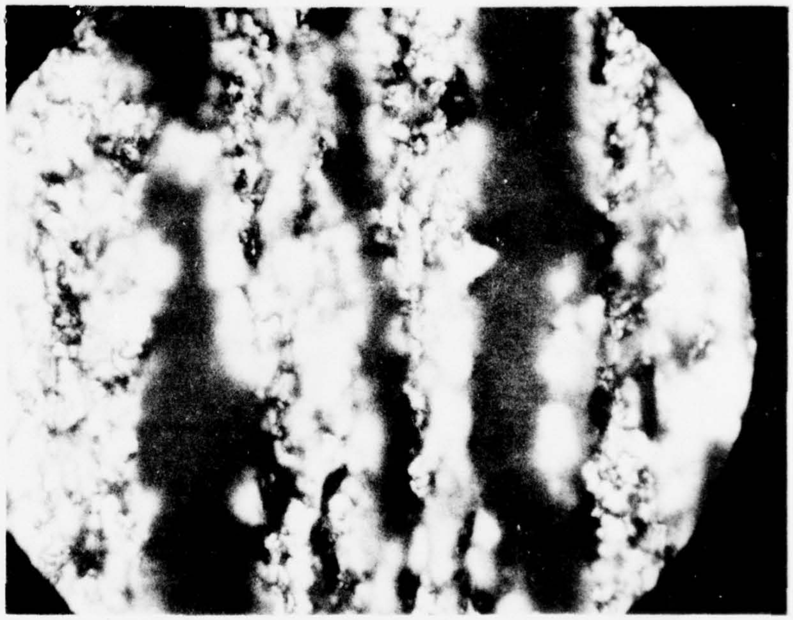


Fig. 4-13 Same as Fig. 4-10 at magnification of 1000X.

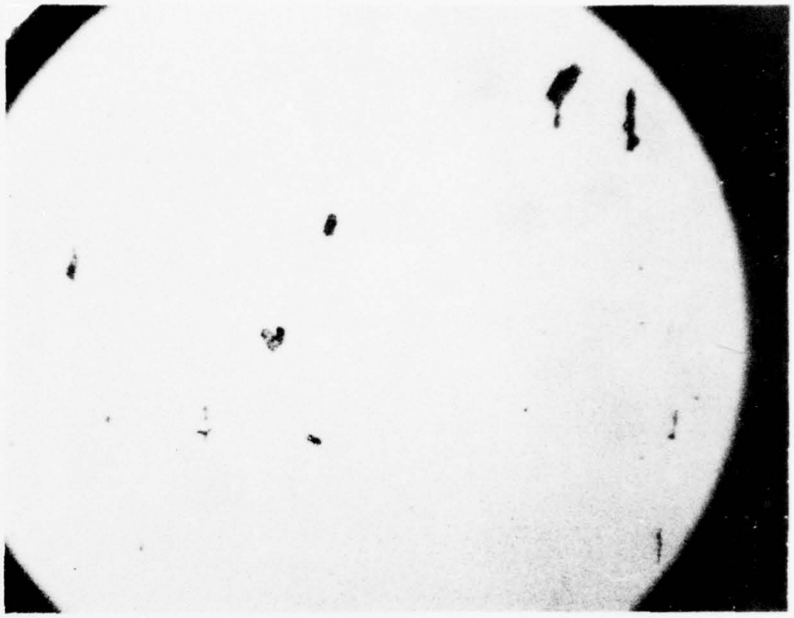


Fig. 4-14 Entry deposit of ferrogram made from clean, unused Quaker State 10W-30 oil taken directly from can. Magnification 100X.

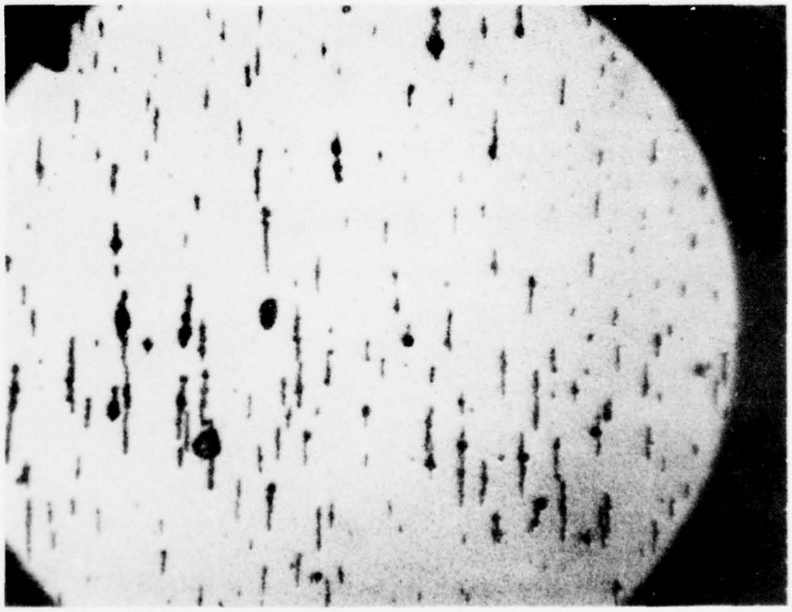


Fig. 4-15 Entry deposit from Quaker State 10W-30 after 5 minutes of circulation through system with magnet and Falex machine off. Particles seen here are left over from prior run. Flow velocity 5.7 cm/sec. Temperature 25°C. Magnification 100X.

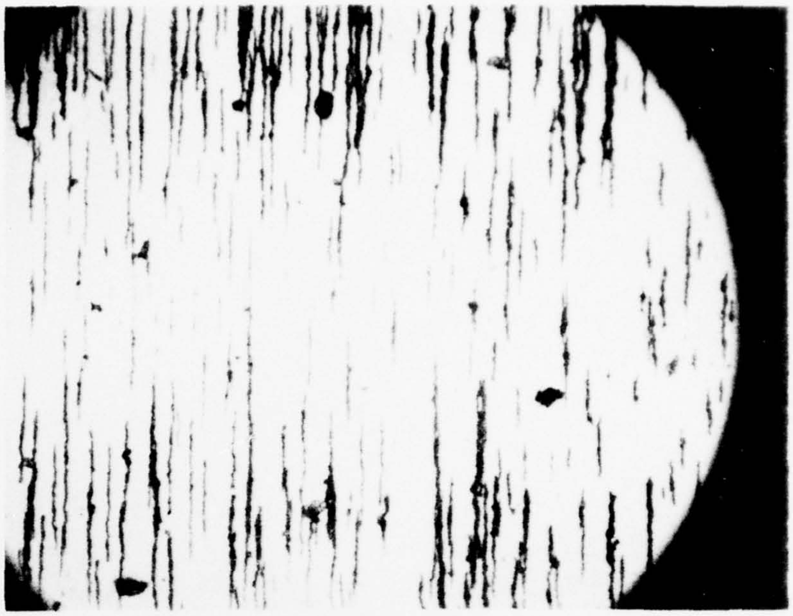


Fig 4-16 Entry deposit after one-half hour of operation of Falex wear particle generator with magnet off. Magnification 100X.

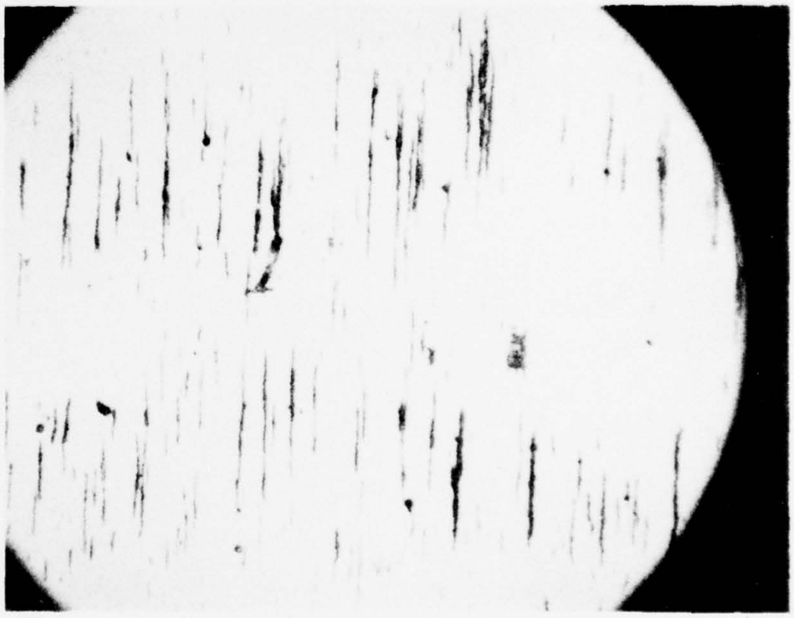


Fig. 4-17 Entry deposit after 5 minutes of magnet operation at 0.25 kilogauss. Wear particle generator still operating. Conditions same as in Fig. 4-15. Magnification 100X.

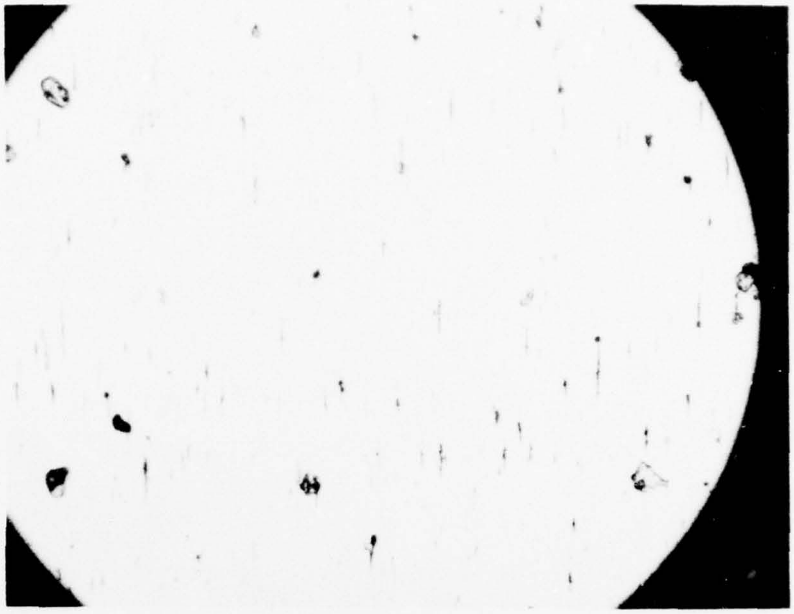


Fig. 4-18 Entry deposit after 5 minutes more filtering at 0.5 kilogauss. Conditions same as in Fig. 4-15. Particle generator still operating. Magnification 100X.

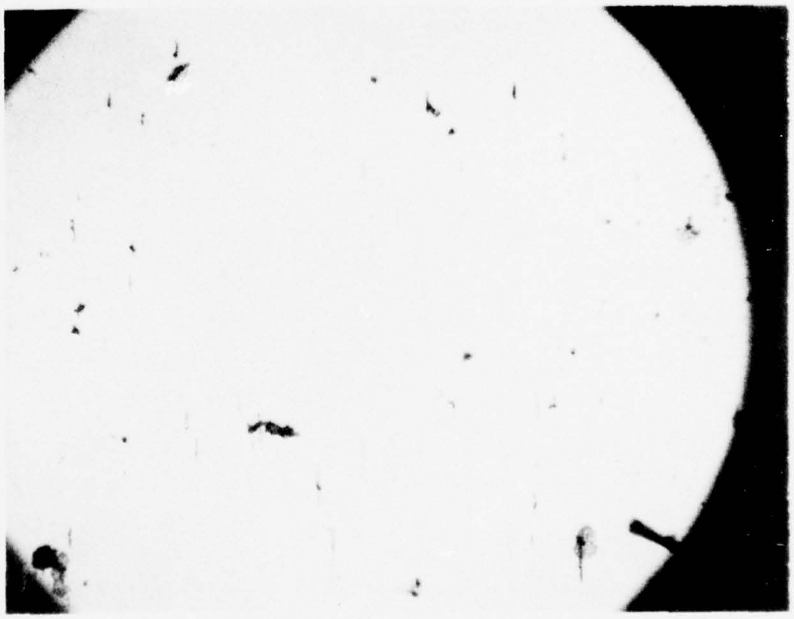


Fig. 4-19 Entry deposit after additional 5 minutes of filtering at 1.0 kilogauss. Same conditions as in Fig. 4-15. Particle generator operating. Magnification 100X.

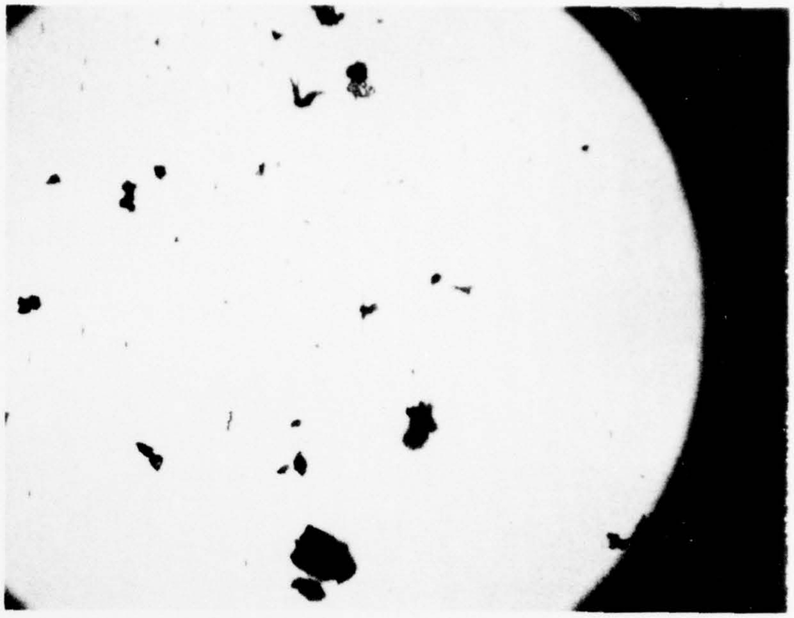


Fig. 4-20 Entry deposit after 5 more minutes of operation at 2.0 kilogauss. Conditions same as in Fig. 4-15. Particle generator operating. Magnification 100X.

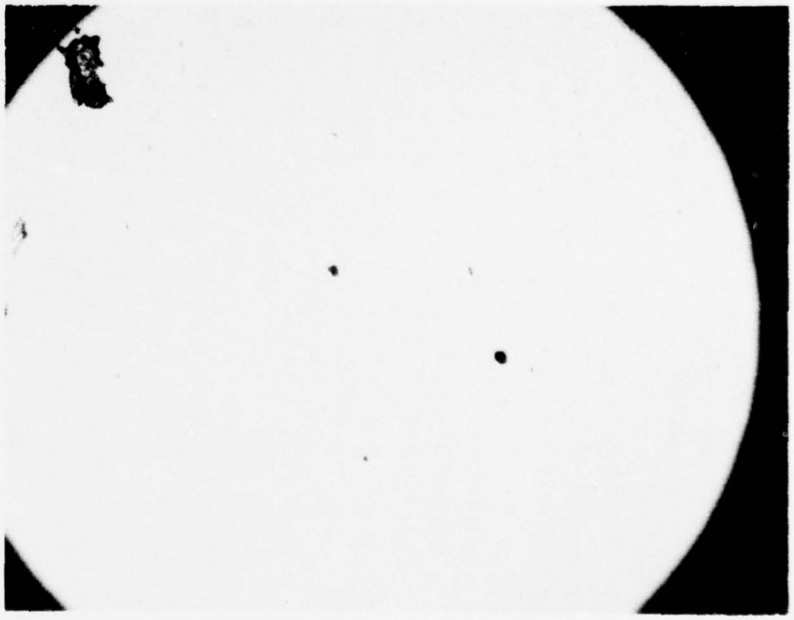


Fig. 4-21 Entry deposit after 5 additional minutes at 2.0 kilogauss with particle generator turned off. Conditions same as in Fig. 4-15 Magnification 100X.

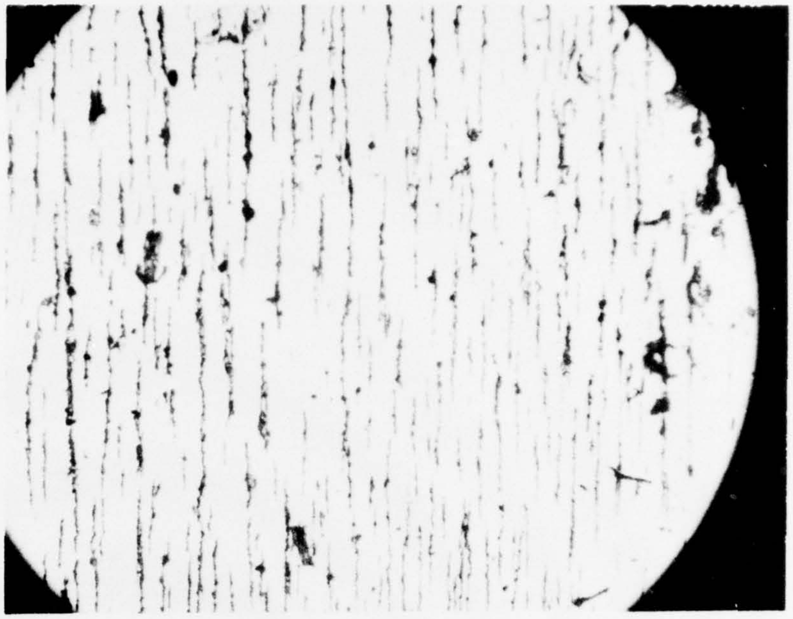


Fig. 4-22 Permanent magnet test. Entry deposit after one-half hour operation of Falex wear particle generator with magnet out of loop. Magnification 100X.

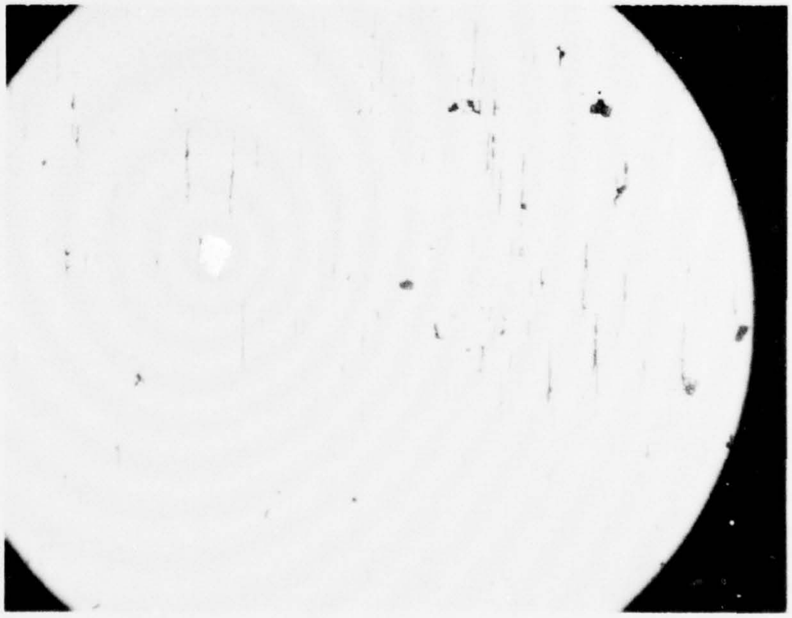


Fig. 4-23 Entry deposit formed after permanent magnet installed in loop and system operated for 5 minutes. Central field of magnet is 0.8 kilogauss. Flow velocity 5.7 cm/sec. Temperature 25°C. Magnification 100X

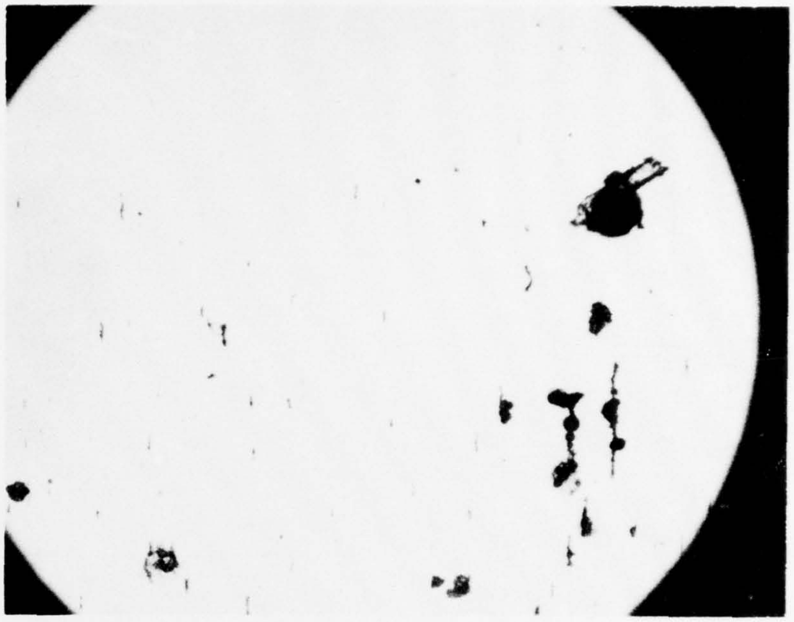


Fig. 4-24 Entry deposit after 5 more minutes of operation with wear particle generator turned off. Conditions same as in Fig. 4-23. Magnification 100X.

5.0 FILTER DESIGN

The tests that have been described in Section 4 clearly demonstrate that efficient removal of ferromagnetic wear particles from lubricating oil by high gradient magnetic separation is achievable with permanent magnet devices. Permanent magnet filters have two distinct advantages over filters equipped with electromagnets: (1) they require no power for operation; and (2), they cannot be inadvertently turned off, thereby releasing back into the lubricant stream the wear particles that have been accumulated. Against these advantages is the disadvantage that a permanent magnet device cannot simply be flushed to remove its accumulated debris, but must be disassembled for cleaning. A permanent magnet arrangement such as the one used in the tests reported herein is easily disassembled for cleaning by simply removing the canister containing the steel wool matrix from the magnet. The magnetic field attainable with such a geometery, solenoidal permanent magnet and insertable canister, is, unfortunately, limited to one kilogauss or less, whereas the tests that have been conducted indicate much better performance can be expected in the 1.5 and 2 kilogauss range.

In view of the above considerations, a considerable amount of thought has been devoted during the course of this work to permanent magnet design improvements that will permit operation at the higher indicated fields and still permit relatively easy disassembly for cleaning or replacement of the matrix element. The result has been an evolution

5.0 FILTER DESIGN (continued)

of three candidate designs that appear to be novel for which patent disclosure documents are being prepared and will be submitted separately from this report.

6.0 CONCLUSIONS AND RECOMMENDATIONS

The work reported here has demonstrated clearly that ferromagnetic wear particles may be removed efficiently from lubricating oils by means of high gradient magnetic separation at a field intensity between 1 and 2 kilogauss. Furthermore, permanent magnet filter designs have been evolved which are extremely flexible in concept for adaptation to a wide variety of specific filtration situations. The task remains, however, of identifying potential applications of this technology, and arranging demonstration tests to establish the validity of the application. Opportunities need to be found to conduct tests supervised by people who are experts in the application, preferably at existing test facilities.

One such opportunity is currently being pursued with Diesel engines. The polymerization and oxidation of Diesel lubricating oil due to high operating temperatures produces substances that rather quickly plug conventional filters. The high gradient magnetic filter appears to offer a means for filtering out the wear particles while permitting these polymerization and oxidation products to pass readily through the filter and thereby avoid blockage. Arrangements are currently being made to test the efficacy of such filtering for wear reduction at the Diesel engine test facility under the direction of Prof. John Johnson at Michigan Technological University in Houghton, Michigan. Prof. Johnson has had many years of experience with Diesel engine engineering and has made use of innovative techniques for determining the amount and location of wear in such engines.

6.0 CONCLUSIONS AND RECOMMENDATIONS (continued)

Other opportunities of this kind are currently being explored in the cleaning of hydraulic and cutting oils, the re-refining of engine oil and lubrication systems for large prime movers. These efforts will continue with emphasis on painstaking performance evaluation in specific applications.

REFERENCES

1. Oberteuffer, J.A., *Magnetic Separation:* A Review *of* Principles, Devices, and Applications, IEEE Transactions on Magnetics Vol. MAG-10 No. 2, June 1974.

2. Scott, Douglas, Seifert, W.W., and Westcott, V.C., The Particles of Wear, Scientific American, Vol. 230, No. 5, May 1974.

APPENDIX I

Falex Procedures for Evaluating Lubricants

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Although bench type lubricant test machines are widely used, they are normally limited to use as rough screening tests. However, with test conditions modified to better simulate service conditions, meaningful test results can be obtained.

Consideration of dilution techniques, analysis of the type of failure of the test pieces, use of the transition pressure as an end point for step-up tests and study of the important property of lubricant anti-weld value are all shown to give correlation between Falex lubricant tests and field service performance. Solid film lubricant testing is summarized.

INTRODUCTION

Laboratory bench test machines can and do give practical and meaningful results in rating lubricants. These results can be shown to correlate with service use of the lubricants if proper test procedures are applied. Unfortunately, there is a general desire to oversimplify these procedures in order to get a single easy rating value. This oversimplification, without further interpretation or investigation of additional properties can severely lower the confidence level in all bench testers. Laboratory bench testing is a necessary tool that must be used since the alternative of full scale service tests is much too time consuming and expensive.

Really reliable service performance data is most difficult to establish. One application may differ widely from another. The bench test procedures must be set up to correlate with the service data available for a given application.

For example, one automotive company found that a sulphurized fatty oil in bright stock gave relatively no field complaints of poor service from a large number of their car dealers. Their use of black transmission oil as original fill resulted in a large number of such complaints. An equal mixture of the two oils resulted in only a few complaints. Conventional increasing load tests on the Falex machine did not give results comparable to these field reports. However, modifying the procedure to show the wear in a three minute period following the high pop-up in torque, or transition pressure, paralleled the field reports of the car dealers. This was a radical departure in procedure from conventional methods, but it correlated with the field data.

Another example: after 10 years of testing on cutting oils, uniformity of results was not obtained until the increasing load type procedure was changed to the 15 minute wear tests, as explained later in the paper. If a bench test does not give a useful evaluation, procedures and other variables must be modified until it does.

Some considerations are suggested herewith for Falex test machine procedures to satisfy the need for more meaningful laboratory tests.

DESCRIPTION

The Falex lubricant testing machine is illustrated in Figs. 1, 2 and 3. The recording instrument in the photograph, Fig. 3, gives a trace of the torque or friction developed during the test and can be used as an automatic cut-off and timer. The test piece configuration is shown in Fig. 2. A ¼ in. steel journal is rotated against two stationary V-blocks to give a four-line contact. The test pieces and their supporting jaws are immersed in the oil sample cup for oil lubricants, or

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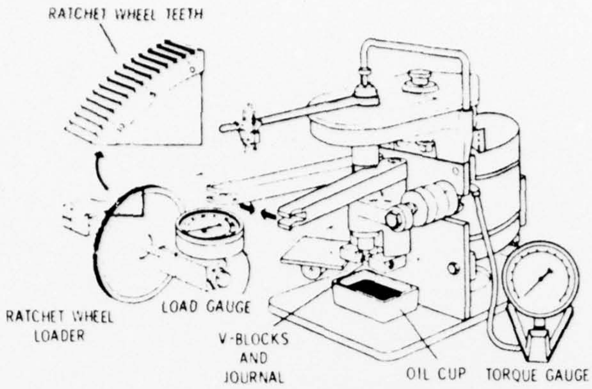

Fig. 1—Schematic diagram of tester.

the test pieces can be coated with a solid film lubricant. The journal is driven at 290 rpm and load is applied to the V-blocks through a nut-cracker action lever arm and spring gauge. The load is actuated by means of a ratchet wheel mechanism that also indicates wear like a micrometer. This micrometer arrangement allows the measurement of wear while the test is in progress. Each 18 teeth on the ratchet wheel equals 0.001 in. of wear. The entire load arm assembly is free to rotate about the main shaft and friction developed during the test is shown in inch-pounds on the torque gauge, or on the recorder chart.

A field calibration method is an important recent development on this machine. This gives the exact load on the test pieces and it is determined by making brinell indentations on copper test coupons of established hardness. The indentation diameter in millimeters is plotted against the gauge load at which they were made. This curve is then compared to the theoretical curve calculated from the brinell formula and constitutes the calibration curve for any machine and gauge combination. Refer to Fig. 4 and Bulletin 5.61 of Falex Instruction Manual (*1*) (*2*) (*3*).

The theoretical brinell curve is used for the 3000 lb and 800 lb, which are direct reading load gauges. However, a slightly modified theoretical curve is used for the 4500 lb gauge which corresponds to the dead weight standard used in calibrating this gauge for many years. The 4500 lb gauge is set up so that it reads the load perpendicular to the bearing face of the V-block, rather than the direct load on the pin. It was felt that too much confusion would result from any attempt to change the 4500 lb gauge standard since there is so much background and data based on the earlier calibration.

Several round robin programs have demonstrated that for a given diameter of brinell impression, all gauges may be used interchangeably on many machines of various ages with good precision results.

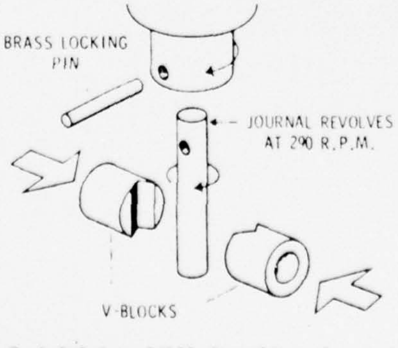

Fig. 2—Exploded view of V-blocks and journal arrangement.

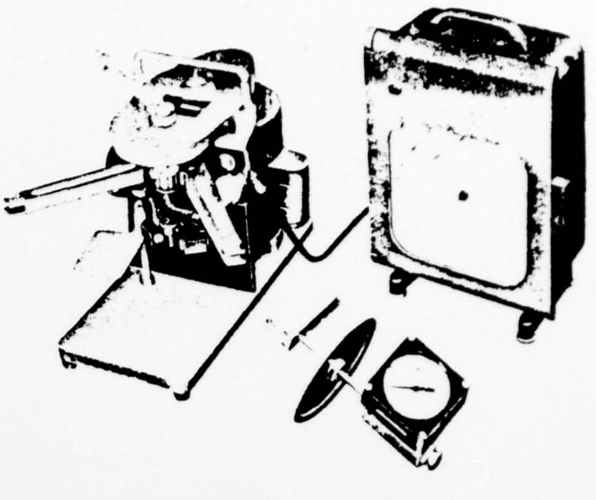

Fig. 3—Test machine with automatic torque cut-off and timer.