# NON-INTRUSIVE ANALYSIS OF CONTAMINANT WEAR IN GEAR PUMPS THROUGH FERROGRAPHY

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## PREFACE

This thesis is concerned with the investigation of the contaminant wear characteristics in hydraulic gear pumps. The wear of any fluid component is difficult to study. First of all, if the process is to be simulated, great care must be taken to insure that the simulated process is representative of the actual process. Due to the complexity of hydraulic components this requirement dictates that the study be conducted on the component while it is operating in a realistic manner. Secondly, because the fluid medium must be contained it is impossible to study the wear process directly. Finally, the third factor is the control of the contaminant which is, in most cases, invisible to the naked eye. The use of flow degradation to evaluate the contaminant wear in hydraulic pumps has provided the technical world with considerable insight into the process. However, little can be learned from such an appraisal concerning the true nature of the contaminant destruction. The introduction of Ferrography has provided yet another dimension to the area of wear analysis. It is truly felt that this technique is capable of producing data which can revolutionize the area of contaminant wear.

It gives me great pleasure to acknowledge my indebtedness to Dr. E. C. Fitch, Jr., for the guidance, inspiration and encouragement he provided during this effort. In addition, I would like to express my gratitude to the other members of my graduate committee composed by Dr. J. E. Bose, Prof. R. E. Chapel, Dr. K. N. Reid and Dr. J. L. Folks for their guidance and patience during my doctoral program. I want to

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# CHAPTER I

## INTRODUCTION

The evolution of high pressure, high performance hydraulic systems accompanied by the inflationary economic spiral has focused considerable attention upon the life and reliability of such systems. The initial cost of modern hydraulic components is high and this cost added to that of maintenance, downtime and repair has created a great demand for hydraulic systems which can survive the rigors of field operation for long periods of time. The field service life of hydraulic components is assessed through their performance. For example, a hydraulic pump is considered "worn out" when it no longer provides sufficient flow at operating pressures. Hence, to be useful any study which is directed toward assessing the potential life of a hydraulic component must be based upon the performance of those components.

Wear is one of the most costly phenomenon which occurs during the use of devices in the world today. The U. S. Navy has reported (1) that the cost of wear control in aircraft and surface ships is approximately 2/3 the cost of the fuel. In many wear processes, especially those occurring in oil wetted components, abrasive particles serve to accelerate the deleterious attack upon critical internal surfaces. In some cases, engineers have learned to harness this phenomenon for the benefit of industry. For example, various manufacturing processes (such as grinding, lapping, sanding, etc.) make good

use of abrasive particles in controlling the rate of material removal and the texture of the finished surface. However, when such processes are undesirable, as is the case in hydraulic components, abrasive particles become contaminants and their effect has fostered an area of engineering science appropriately named contaminant wear.

Three basic modes of contaminant related failures have been defined for hydraulic system components (2) (3)--transient, catastrophic, and performance degradation. Transient failures are characterized by a temporary malfunction, such as an excessive pressure overshoot or a momentary hesitation in response. Such unsatisfactory performance is caused by the presence of contaminant particles lodged in critical clearances of a component causing increased drag forces or a temporary configuration change between mating parts. Catastrophic failures, on the other hand, occur suddenly and are of a permanent nature. This type of failure may be typified by a complete locking of moving parts (such as directional valve spools or relief valve poppets)--a condition normally referred to as contaminant lock (4). In many components, contaminant particles can plug small orifices which control critical hydrostatic balances. When this occurs, the balance is lost, and an almost immediate catastrophic failure will follow.

While both transient and catastrophic failures certainly reduce the life and reliability of hydraulic systems, it is almost impossible to treat them as wear processes. Performance degradation is the only basic contaminant related failure mode which predominatly occurs as a result of a wear process. Such a failure results when the performance of a hydraulic component is impaired to such an extent

that it must either be repaired or replaced. The characteristic feature of this failure mode is the gradual but persistent deterioration of critical surfaces within the component. In the case of hydraulic gear pumps, a prolonged attack by particulate contaminants will result in an enlargement of the leakage paths inherent to the pump. The larger paths will accommodate an increased leakage flow, which will be reflected in a lower output flow from the pump. In addition, the wearing away of these critical surfaces will be accompanied by the generation of debris which adds to the particulate matter already entrained in the system fluid.

Caused by a combination of abrasion and erosion, contaminant wear is defined as the process through which performance degradation occurs due to the presence of particulate contamination (5). Obviously, the end result of contaminant wear in a hydraulic component is a performance degradation failure. In order to achieve a long service life from a hydraulic system it is necessary to protect the components from particulate contaminants. Such protection is provided in a well designed hydraulic system by a filter. However, before a filter can be properly selected the degree of protection required by the system components must be evaluated (6).

The contaminant protection level required by a system to minimize contaminant wear will be dictated by the component which exhibits the highest sensitivity to the entrained contaminants. The three most critical types of components in a hydraulic system (from a performance standpoint) are the pumps, valves, and cylinders. Normally valves and cylinders are characterized by low relative velocities between sealing surfaces and/or elastomeric seals. However, the high pressure/

low pressure sealing in most hydraulic pumps is typified by close tolerance metal mating parts. This metal to metal sealing area is subjected to both high pressure gradients and high relative velocities. Therefore, the hydraulic pump is the likely candidate for the most contaminant sensitive component in a hydraulic system. Experience bears out this conclusion. In addition, the widespread use of the gear type hydraulic pump in the fluid power industry makes it an obvious choice for contaminant wear studies.

The configuration of the leakage paths in a hydraulic gear pump is complicated and the contaminant wear process is difficult to simulate without actually operating the pump in a controlled contaminant environment under realistic conditions. This means that the evaluation must be made with the pump in a circulating hydraulic system. Basically wear analysis methods which could be used in such a situation can be classified as either intrusive or non-intrusive. Intrusive techniques rely upon metrological evaluations (direct meaurement of surface changes), while non-intrusive approaches include direct performance degradation measurements and/or wear debris evaluation. While intrusive techniques may be valuable to the pump designer they have not been widely employed for gear pump evaluations mainly due to the problems of disassembling the pump, making microscopic measurements, and attempting to relate these with performance. The non-intrusive method employing direct performance monitoring has gained the most popularity for evaluating contaminant wear of hydraulic gear pumps. However, this approach has the disadvantage of relying upon gross component destruction to produce sufficient surface deterioration for accurate detection and appraisal.

Wear debris analysis is a non-intrusive wear analysis technique which has been applied much more to lubrication systems than to hydraulic systems in the past. Spectrometric analysis of the fluid from an oil wetted component produces information relative to the elemental composition. However, the equipment necessary to conduct spectrometric analysis is sophisticated and expensive and recent studies (7) indicate that such analysis may not produce all of the necessary information associated with wear processes. A relatively new technique to isolate and evaluate the wear debris entrained in the fluid of a lubrication or hydraulic system is based upon a technology called Ferrography (8). Basically, the Ferrographic Oil Analysis System employs a flowing stream in which entrained particles are subjected to a combination of magnetic, gravitational and drag forces. By design, the magnetic field is the most dominate and causes the separation of magnetically active particles from the fluid and environmental contaminants (9). Once isolated, the amount of debris is used to assess the severity of the wear process, while the size, shape, structural appearances, etc. of the debris provide valuable information relative to the dominant wear mode.

The capability of the ferrograph to separate magnetically active particles from other particulate contaminants which are present in the oil of a hydraulic system, make this technique uniquely suited to contaminant wear studies. In such investigations, wear is induced by means of a non-magnetic test contaminant. Without a technique to separate the generated debris (which is, in general, magnetically active) from the introduced test contaminant, wear debris analysis of contaminant induced wear would be virtually impossible. Previous

investigations by the author using the Ferrographic oil analysis system procured by the Fluid Power Research Center indicate that the method is potentially capable of measuring the wear debris generated during a contaminant test on a hydraulic gear pump.

The proposition examined in this dissertation is that the amount of debris generated and the reduction in output flow during the contaminant wear process are both related to the enlargement of the critical leakage paths within a hydraulic gear pump. Since the leakage paths of such a pump are numerous and complex, a simplified pump model is used in which the various leakage paths are lumped and described by the flow between two flat plates in relative motion. The use of such a pump model provides a characteristic clearance as an intermediate parameter which is employed in formulating the relationship between flow degradation and wear debris generation. Inherent in the proposition is the postulation that the Ferrographic technique is capable of accurately measuring the amount of wear debris generated.

In order to support this proposition for gear pumps, it is necessary to relate the amount of contaminant induced wear debris as measured ferrographically to the increase in leakage through a consideration of the characteristic clearance parameter of the pump model. Based upon earlier investigations by the author, it is reasonable to expect that the Ferrographic data will provide a greater degree of resolution than the flow degradation measurements commonly used in contaminant sensitivity evaluations. This greater resolution will essentially eliminate the need to accelerate the contaminant wear process through the use of excessive contaminant concentration.

This research should (1) advance a new contaminant wear analysis

technique for fluid power components, (2) verify this method for hydraulic gear pumps, (3) provide a better understanding of the process of contaminant wear in the clearances of gear pumps, (4) advance a procedure which can be used to evaluate the contaminant sensitivity of a gear pump at several different operating conditions (such as speed and pressure) using only one test specimen.

The next chapter discusses the concepts associated with contaminant wear and outlines the previous investigations. Chapter III is devoted to the ferrographic analysis technique. The analytical expressions required to transform ferrographic data to flow degradation are developed in Chapter IV while Chapter V delineates the experimental verification associated with these equations. In Chapter VI the significance of the research is discussed and recommenations for additional studies are presented. Chapter VII provides a summary along with specific conclusions resulting from this research investigation. The appendices contain the actual data measured as a result of this research effort.

## CHAPTER II

## PREVIOUS INVESTIGATIONS

The interrelated processes of friction and wear along with the influence of lubrication have been recognized since ancient times (10). The use of lubricants by the Egyptians in the transport of large building blocks probably reduced the coefficient of friction and hence the labor force by about fifty per cent. The early attempts to develop rolling-element bearings in Greek and Roman times is indicative of a desire to replace sliding by rolling contact and thus reduce friction and wear in machinery. Many of the changes in bearing materials recorded were beneficial in decreasing friction, although the main incentive responsible for the change was probably a desire to reduce the excessive wear of vital machine parts. In some instances, as in the case of the early wheeled vehicles and the potter's wheel, leather seals were employed. This indicates that these early engineers recognized the deliterious effects of contaminant wear due to free particles entrained in the bearing lubricants.

In general, scientists have divided the phenomenon of wear into several separate types (11) (12). These wear mechanisms were given by Rabinowicz (12): as follows:

1. Adhesive or Galling Wear
2. Abrasive or Cutting Wear
3. Surface Fatigue

4. Erosive Wear

5. Corrosive Wear

6. Cavitation Wear

It is common practice for laymen in the area of contamination control to equate abrasive wear and contaminant wear. This does not, however, provide a clear picture of the phenomenon called contaminant wear. Abrasive wear is normally divided into processes termed two-body and three-body (13). Two-body abrasion refers to the case where there are only two surfaces involved and micro-cutting takes place due to surface asperities. Three-body abrasion is meant to imply the presence of a third member in the process (namely, a defiling particle). Obviously, contaminant wear does not encompass that process called two-body abrasion. Actually, contaminant wear is the result of two types of wear acting simultaneously--three-body abrasion and erosion, where erosive wear is characterized by the collision of free moving contaminant particles with the critical component surfaces.

The most comprehensive studies on three-body abrasion has been reported by Rabinowicz et al. (14). The work by Rabinowicz was prompted by eariler tests conducted by Toporov (15). Rabinowicz utilized a specially designed abrasive wear machine to produce results relative to three-body abrasion using various exposure times, material hardness, and abrasive grain size. From this study, it was concluded that the prevailing phenomenon was similar to those of two-body abrasion using metal specimens sliding against abrasive-covered paper. In comparing his results to those obtained in two-body abrasion tests it was found that abrasive wear rates during 3-body abrasion are about 10 times less during 2-body abrasion.

The results of two-body abrasion using abrasive covered paper were reported by Nathan and Jones (16). The paper presented by Nathan and Jones contended that there were many inconsistencies in the abrasive wear of metals as determined by different authors which necessitated a detailed investigation to determine the relationships existing between the abrasive wear of metals and the experimental parameters which influence abrasive wear. The conditions studied by Nathan and Jones included:

1. Applied Load
2. Length of abrasive path
3. Mean diameter of abrasive particles
4. Velocity of the abrasive surfaces
5. Different types of abrasive particles
6. Temperature of the environment
7. Absolute humidity of the atmosphere

Of particular interest here is the results obtained by Rabinowicz using various particle sizes (abrasive grain sizes) and the results reported by Nathan and Jones with various applied loads, diameter of abrasive particles and velocity of the abrasive surfaces. Both of these investigative teams concluded that abrasive wear rates increased linearly up to a particle size of 70-80 micrometres. Above that size Rabinowicz contended that wear rates were independent of abrasive grain size while Nathan and Jones showed a greatly reduced dependency. In considering the conclusion that abrasive wear is linear with particle size below 80 micrometres, it must be noted that both of the referenced investigators used only two particle size values below that limit and evaluation of the curve fits presented indicate a rather poor correlation

to this linear representation. In fact Nathan and Jones stated that the abrasive wear obtained for abrasive sizes of 35 and 45 micrometres were less than the expected values for the linear relationship.

The experimental data acquired by Nathan and Jones using different applied loads indicate that abrasive wear increases with increasing load. In addition, the results obtained when the relative velocity of the wear surfaces was varied showed essentially no effect due to the speed parameter. Thus, based upon the data presented by both Rabinowicz and Nathan and Jones, the curves shown in Figure 1 should generally describe the results of a contaminant wear test on a hydraulic pump. In this figure pressure 1 is greater than pressure 2 and it has been assumed that applied load as presented by Nathan and Jones would equate to pressure in a hydraulic pump. Also, since the rotational speed of the pump can be equated to the relative velocity of the wearing surfaces, there should be no influence of speed in contaminant wear of a pump.

The erosive wear phenomenon which is believed to be an integral part of the contaminant wear process has been investigated by numerous researchers (17) (18) (19) (20) (21) (22). In general, it has been concluded that the volume of material removed from a surface due to erosion is a function of the mass of the impinging particles, the particle velocity, the threshold of deformation for the wearing surface and the amount of energy needed to remove one unit volume of material. This relationship can be written as follows:

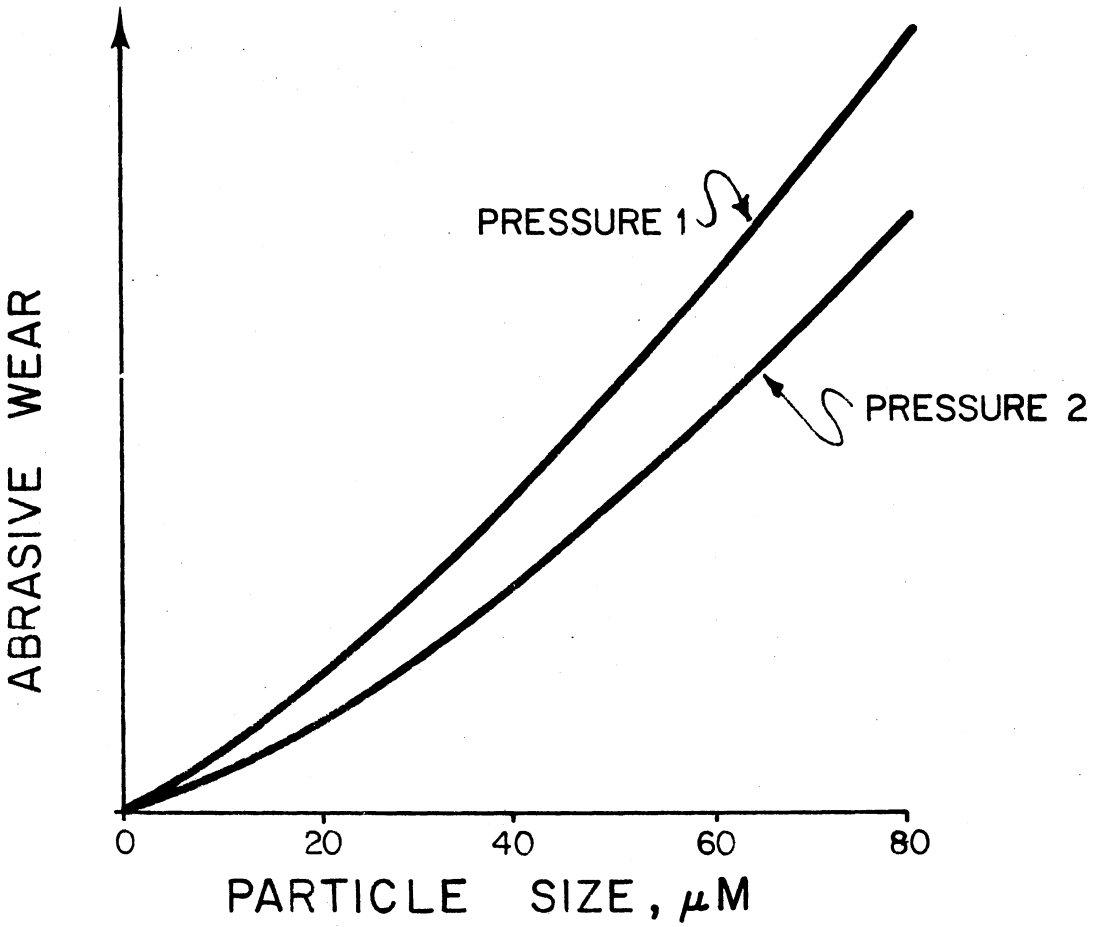


Figure 1. Expected Results for Contaminant Wear Tests on Hydraulic Pumps (Adapted from References 14 & 16)

$$V = \frac{1}{2} \frac{M[v - k]}{E} \qquad (1)$$

where: V = wear volume

M = total mass of material impinging of the surface

v = velocity at collision

k = threshold of deformation

E = amount of energy needed to remove one unit volume of material

Since for a hydraulic pump exposed to particles entrained in the circulating fluid, the particle mass is small while the threshold of deformation and the magnitude of energy is high. Thus it must be logically concluded that the volume of wear removed by erosion would be small compared to that removed by abrasion. Hence, the dominant mode of the contaminant wear process is abrasion.

While the results obtained by these experimental tribologists have provided considerable insight into the contaminant wear situation, their work left much to be desired in the application to a complex component. The primary means of measuring the amount of wear incurred during any of the tests was by weighing or dimensional changes of the wearing surfaces. This is expedient and straight forward when small test specimens are used. However, this method of measuring wear for a complete component such as a hydraulic pump is totally inadequate. To assess wear in a hydraulic pump through such intrusive means, it would be necessary to disassemble the pump after any contaminant exposure, identify the microscopic changes which have occurred and measure them. Furthermore, if the decision was made to continue testing with the same pump, it would have to be reassembled with no guarantee that the process would not have been

irreversibly altered.

Another dilemma which faced hydraulic system engineers in applying the work of these fundamental wear researchers lies in the transformation of the results of basic wear tests into performance of hydraulic components. For example, the main performance parameter for a hydraulic pump is output flow. If there was a transformation which converted the abrasive wear as shown on the vertical axis of Figure 1 into change or degradation in flow rate, the problem would not exist. However, such a transformation does not currently exist and the results reported in terms of volume of material removed from test fixtures can be used only for guidance in design. It should be noted that most of the efforts reported in the area of 2-body and 3-body abrasion were conducted to gain knowledge concerning grinding, lapping, etc. processes used in manufacturing. In this regard the work is invaluable.

In order to evaluate contaminant wear in a hydraulic component, it was necessary to develop a technique which provides a wear parameter that could not only be measured non-intrusively but also one which could be related to some critical performance variable. Research work which introduced and fostered this philosophy was reported by Wolf (22) at Oklahoma State University. Wolf correctly recognized that the effect of particulate contamination was to enlarge the leakage paths of a pump. This enlargement would be accompanied by increased leakage rates which would be reflected by decreased output flow from the pump. The output flow of the pump could indeed be measured non-intrusively and was, in fact, the primary performance variable of the component. To avoid confusion with wear tests designed to evaluate wear in terms of dimensional changes or weight loss, Wolf used the term contaminant

tolerance and contaminent wear to imply performance degradation as a result of contaminant action.

In the work conducted by Wolf, test pumps were subjected to various types, concentrations, and particle size increments of contaminants. The pumps were operated continuously at constant values of speed, temperature and pressure, while flow degradation was measured for each contaminant exposure. The objective of this activity was to determine the sensitivity or tolerance of a given pump to various contamination levels in order to provide a filter selection basis. In 1967 Hollinger (23) reported on the results of tests similar to those conducted by Wolf. In both efforts, it was concluded that leakage flow measurement or output flow degradation was a reasonable technique for evaluating contaminant wear and that AC Fine Test Dust classified into various particle size increments produced the most change in the leakage of a hydraulic pump.

Later, in 1970, research work by McBurnett (24) proposed a contaminant sensitivity test similar to that advanced by Wolf, except that it now incorporated a multi-passing of the injected contaminant instead of a single pass. Also, instead of using de-ironized AC Fine Test Dust (ACFTD) classified into five micrometre increments (0-5, 5-10, 10-15, etc.), McBurnett's efforts utilized particle size ranges (0-5, 0-10, 0-20, 0-30, and 0-40 micrometres). These size exposures were repeated three times unless the output flow of the pump degradated by more than 30% from its initial value.

The first attempt at advancing a mathematical expression for the contaminant sensitivity of a pump was reported in 1971 by Fitch and Maroney (25). In 1972, Bensch and Fitch (26) further modified the pump

contaminant test by incrementally subjecting the test pump to a single set of increasing particle size ranges involving a circuit shown schematically in Figure 2. The particle size ranges (0-5, 0-10, 0-20, 0-30, 0-40, 0-50, 0-60, 0-70, and 0-80 micrometres) were obtained from ACFTD and injected at a gravimetric level of 300 milligrams per litre. After each contaminant exposure, the output flow was precisely measured and normalized by the rated flow of the pump to obtain the flow degradation ratio. Figure 3 illustrates the performance degradation signatures for three typical pumps where $Q_f/Q_r$ is the flow degradation ratio as introduced by Bensch and Fitch (26). Through industrial guidance Fitch (27) then found that curves of flow degradation ratio versus particle size could be linearized by using log-normal model. Figure 4 shows the same typical pumps as used in Figure 3 plotted as a log-normal model. The concepts and relationships presented by Bensch and Fitch (26) and Fitch (27) were used by Fitch and Tessmann (28) to evaluate pumps in general which represents the latest advances in the contaminant sensitivity of hydraulic pumps.

The primary disadvantage of the contaminant sensitivity work which has been accomplished to date is that an extremely high contamination concentration (300 mg/l) must be used for each particle size range in order to obtain sufficient flow degradation over the spectrum of sizes. Such a concentration is higher than the majority of hydraulic pumps would be expected to encounter and results in the complete destruction of most pumps at only one operating condition (speed, pressure, etc.). In addition, the results of mechanism tests as presented by Rabinowicz et al. (14) and Nathan and Jones (16) are difficult, if not impossible, to use in the assessment of performance degradation. On the other

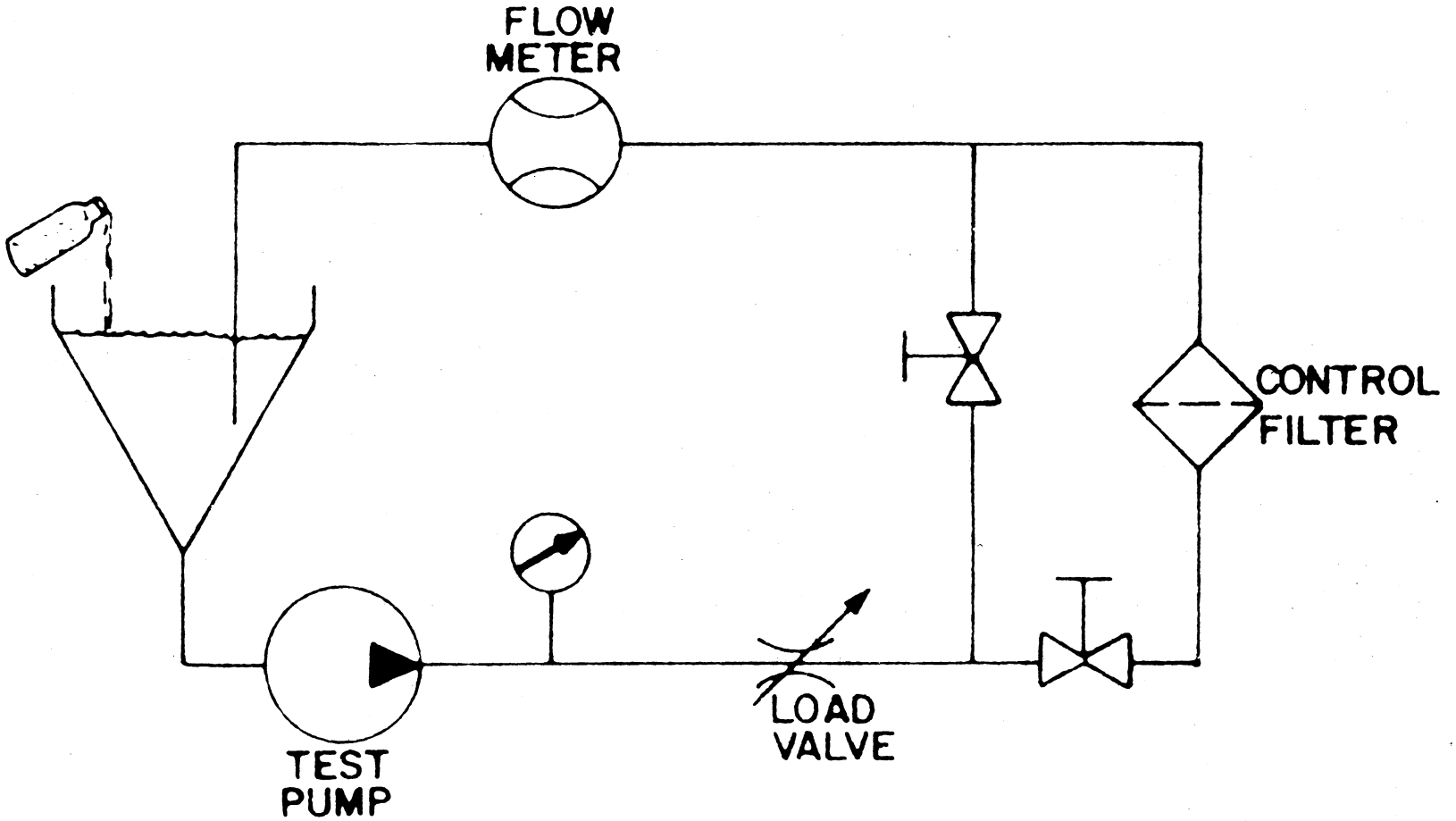


Figure 2. Schematic of Typical Contaminant Sensitivity Test Circuit

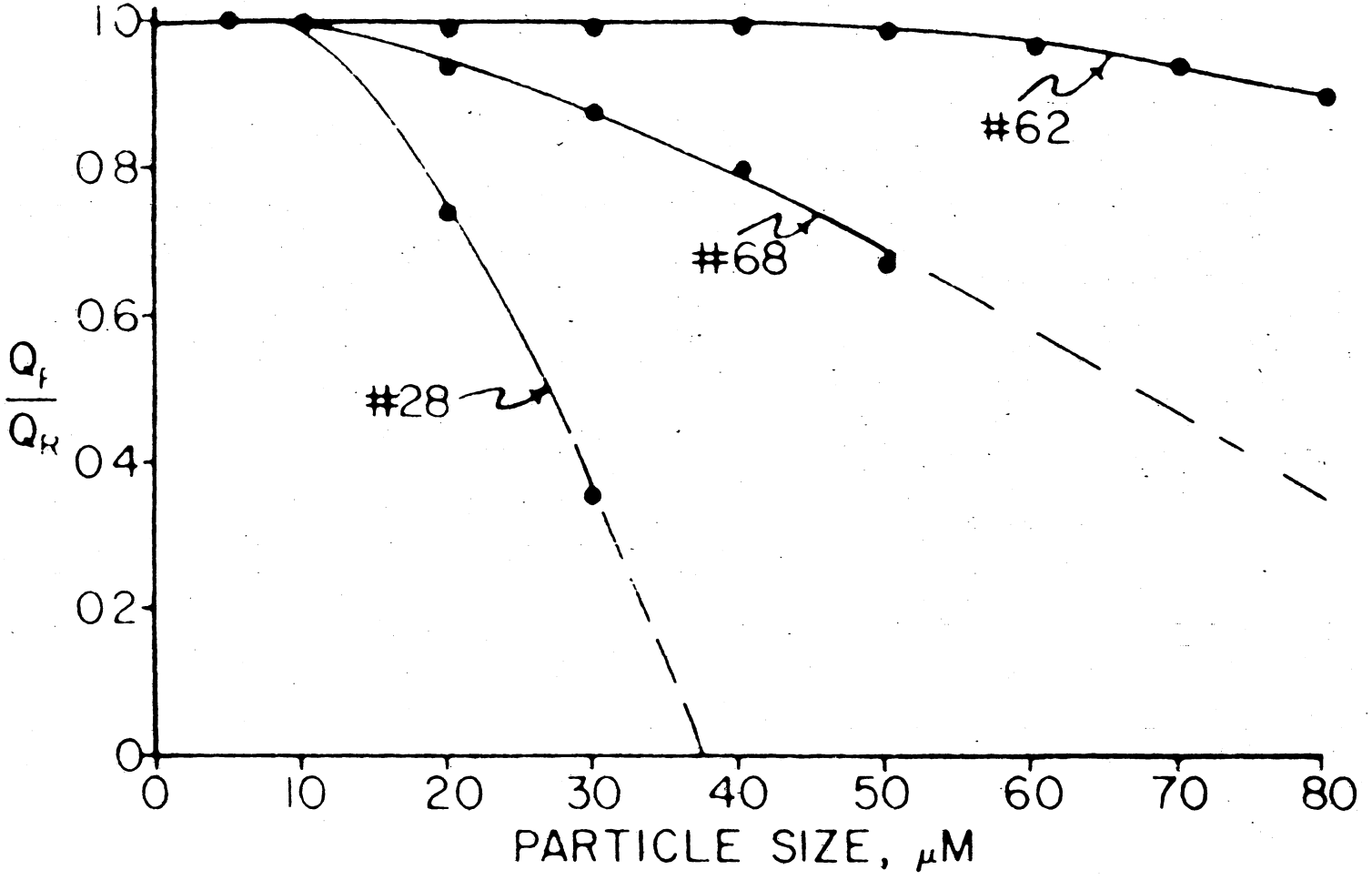


Figure 3. Flow Degradation Signatures for Typical Pumps

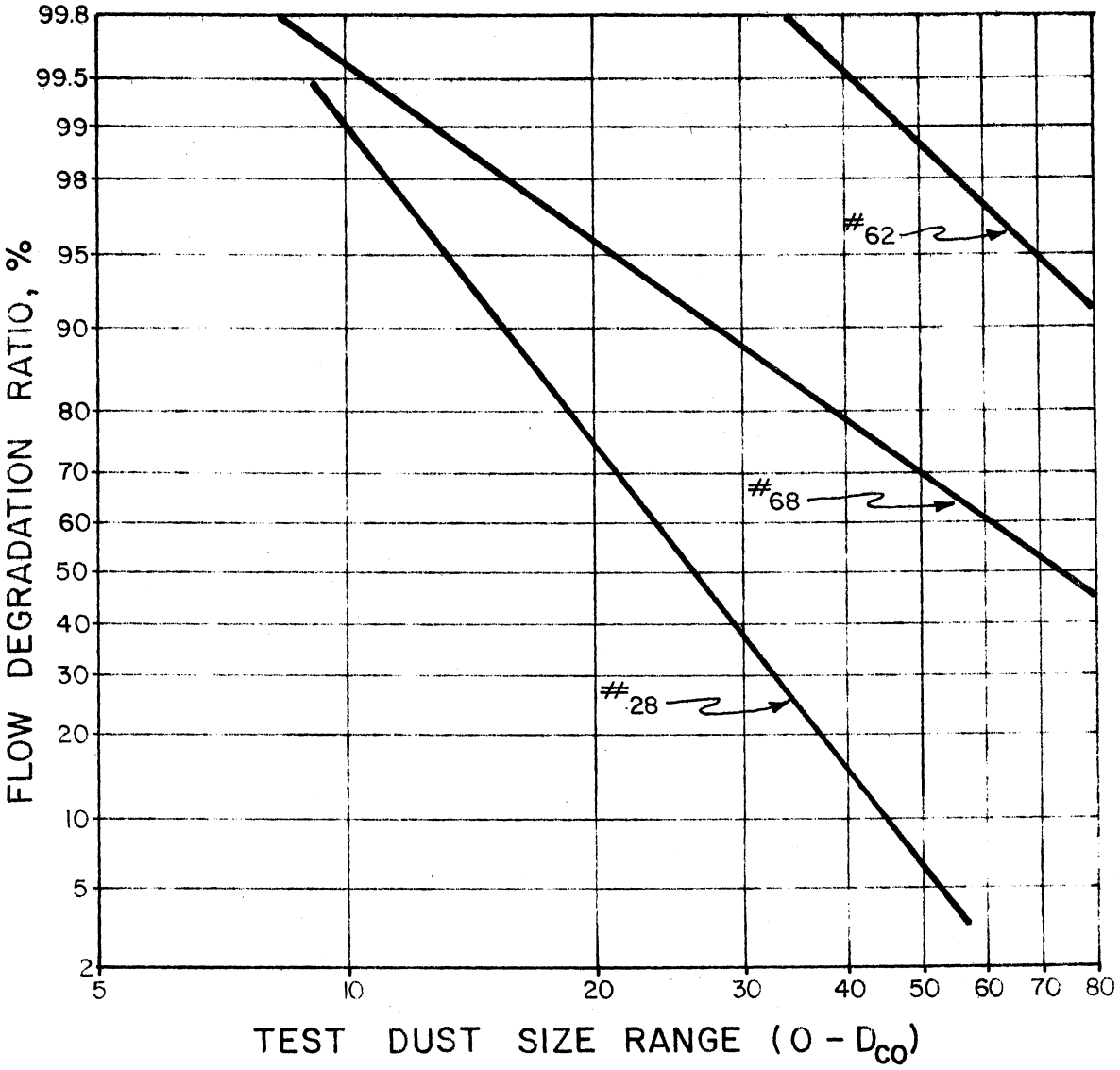


Figure 4. Log-Normal Model for Pump Performance Degradation Signatures

hand, direct performance degradation measurements provide little or no information relative to the nature of the contaminant attack. The answer to this dilemma is to develop a more responsive wear measurement technique which is non-intrusive and can also be related to both surface destruction and performance degradation.

The most likely candidate technique for contaminant wear analysis is associated with the evaluation of the products of the process--namely the wear debris. There are several wear debris analysis techniques which have been applied in various wear evaluation methods. The most widely used apparatus currently is the spectrometer. This device provides data on the elemental constituents of a fluid sample. While there is no doubt that fluid sampling and analysis methods are non-intrusive, there is sufficient evidence (7) which indicates that the spectrometer will not adquately assess a contaminant wear process. In fact, E. L. Falendysz, Director of Hydraulic Laboratories, J. I. Case (29) vehemently stated, "Spectrometric analysis alone is of little value in wear evaluations of hydraulic systems." In addition, Mr. B. L. Poppert, Naval Air Systems Command, AIR-340E, Washington, D.C. at a tribology workshop (30) (31) reported that his sponsored research has revealed critical inadequacies in the spectrometric methods.

Two other wear debris analysis methods which merit consideration for contaminant wear evaluation are the radioactive tracer and the neutron activation techniques. Both methods rely upon nuclear activation. In the radioactive tracer method the wearing parts are nuclearly activated prior to assembly. Then the degree of radioactivity in the circulating fluid is a measure of the amount of material which has been removed from the critical parts. While this techniques has been used on

combustion engines, no record has been found of application to hydraulic components. Undoubtedly, the instrument investment compared to the component costs makes the radioactive tracer technique extremely impractical.

The neutron activation method of wear debris analysis was perfected and has been successfully applied by the Tribology Laboratory at the Research Institute for Automotive Industry (RIAI) in Hungary. In personal conferences with Dr. J. Fodor, Leader of the Tribological Laboratory at RIAI the method was described. In this technique the wear debris is meticulously separated from the vehicle fluid and nuclearly activated, producing radioisotopes of the elements present in the debris. To accomplish this, the debris entrained in an oil sample is collected through a suitable filtration process and placed on the neutron flux of a nuclear reactor. After the activation process, the elemental composition of the debris is measured quanitatively using neutron activated etalons. Using computer aided techniques, the rather laborious measurements can be made rapidly. Although this technique is purported to be extremely sensitive to small amounts of wear from a critical surface, the equipment investment and the time required to perform the analysis render it completely unfeasible for the study of contaminant wear in hydraulic components.

Ferrographic wear debris analysis represents a relatively recent breakthrough in wear assessment technology. Capitalizing upon the magnetic properties (8) of the tiny wear particles, the method isolates the wear debris present in an oil sample from extraneous debris (such as ACFTD used to produce a contaminant wear situation) and the vehicle fluid. The debris thus separated is deposited upon a specially prepared

substrate where the quantity and characteristics can be measured through optical means. A Ferrographic Oil Analysis system was procured by the Fluid Power Research Center in 1975 and has been used since that time for wear evaluation (32) (33) (34) (35) (36). Based upon the results of these studies, it was felt that the Ferrographic technique represented the most practical and feasible approach to a more sensitive contaminant wear evaluation of a hydraulic component on a non-instrusive basis.

# CHAPTER III

## EVALUATION OF THE FERROGRAPHIC ANALYSIS METHOD

Ferrography is a technique developed to separate wear debris from a vehicle liquid and arrange it according to size on a transparent substrate for examination through optical or scanning electron microscopy (37). Although the Ferrographic oil analysis system consists of several features only those pertinent to this research effort will be discussed. Basically, the components of the Ferrographic system used consisted of two major components--a slide Ferrograph or Ferrograph analyzer and a Ferrogram Reader. The Ferrograph Analyzer shown schematically in Figure 5 utilizes a specially developed magnet, which generates an ultra-high gradient field near its poles to force the wear particles to precipitate from the vehicle liquid. A chemically treated microscope slide is placed at an incline to the magnet and acts as a substrate upon which the wear debris is collected. A carefully controlled pressure head on the fluid is used to continually pass a low velocity stream longitudinally along the slide. After a prescribed amount of liquid has been pumped across the slide a washing and fixing cycle removes the residual oil and causes the wear particles to adhere permanently to the slide. The amount of wear debris deposited on the slide or Ferrogram is analyzed through the use of a densitometer (Ferrogram Reader).

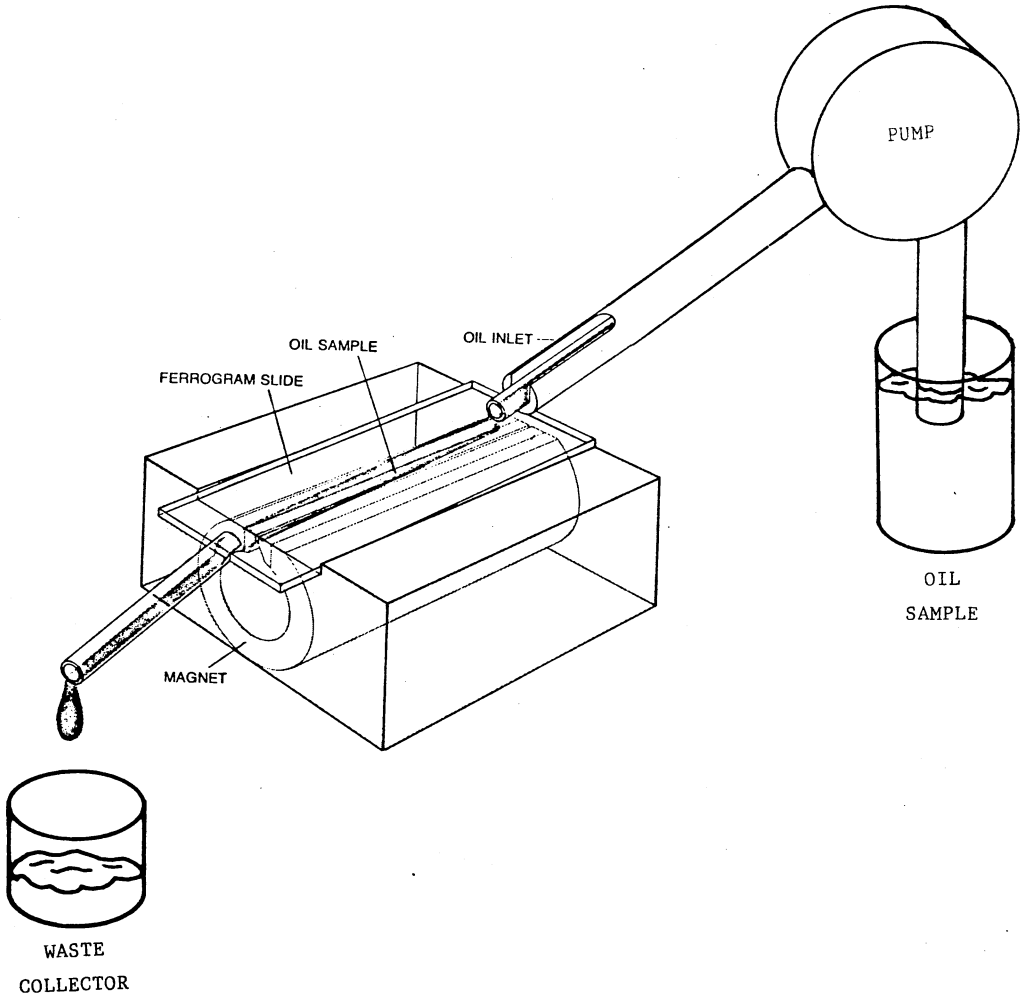


Figure 5. Schematic of Slide Ferrograph

Due to the forces acting on the wear particles as they pass along the length of the substrate, wear debris is deposited all along the fluid path. The Ferrogram Reader, consisting essentially of a controlled light source and a photo cell, is capable of providing optical density readings at various positions along the Ferrogram. Theoretically the density readings along the Ferrogram are a function of the particle size distribution of the wear debris since larger particles will tend to deposit sooner than smaller ones. The density readings obtained are identified by their location on the Ferrogram. For example, the sample flow is started on the Ferrogram at approximately 57 millimetres from the exit end. A density value designated as D54 indicates that it was made 54 millimetres from the exit end of the Ferrogram. In research work prior to this effort, it was found that the debris density at the 54 millimetre location was the most responsive to the contaminant wear of hydraulic pumps (33).

In 1970, Dr. W. W. Seifert, professor of Engineering at Massachusetts Institute of Technology and Mr. V. C. Westcott, of Foxboro/Trans-Sonics, began to look for a simple method of detecting wear in machine parts (8). Joined later by Dr. Douglas Scott of the National Engineering Laboratory at Glasgow, Scotland this team of investigators discovered the unique magnetic properties of the wear debris normally found in fluid systems. According to Scott et al. (8), studies showed that the very small wear particles have only one magnetic domain or at most a few domains and hence they are among the most powerful magnets in existence. As a result of the discovery of the unusual magnetic properties of wear particles, this research team developed the instrument package that has come to be known as the Ferrographic Oil Analysis System. Since the

wear particles are precipitated magnetically, virtually all of the unwanted particles (such as the AC Fine Test Dust used to produce a controlled contaminant wear process) in the fluid sample are eliminated. A more detailed description of the Ferrographic technique and associated equipment is given in Ref. 9.

## Operational Procedures

There are two distinct steps in obtaining Ferrographic density readings. One step involves the preparation of the Ferrogram while the other deals with the actual optical density measurement. To prepare a Ferrogram the fluid sample is agitated vigorously to insure uniform dispersal of the entrained debris. It has been found that heating the sample prior to agitation will enhance the dispersion process. A carefully measured volume of liquid is drawn off and placed in a clean sample bottle along with a volume of a chlorinated hydrocarbon called a fixer. The proportion of sample to fixer is normally 3 to 1. This mixture is shaken and placed on the Slide Ferrograph.

A specially cleaned and prepared substrate is placed in the slide holding fixture of the Ferrograph. The substrate is marked to insure proper placement since it has been coated with a barrier film to insure the correct channeling of the fluid stream. A delivery tube which has been accurately cut for length and has been precleaned is placed into the sample bottle containing the mixture of sample fluid and fixer, positioned in a tube pump, and attached to the delivery arm of the Slide Ferrograph. The delivery arm is then lowered until the delivery tube contacts the substrate and the tube pump is energized. The tube pump is run until the sample bottle is empty to insure an exact volume

of sample fluid has passed across the slide. The delivery tube is then transferred to a bottle containing only the fixer solution and the washing cycle is begun. When the correct amount of fixer has been pumped over the Ferrogram, the tube pump is stopped and the delivery arm is raised from the substrate immediately. The Ferrogram is thoroughly dried with the aid of a high intensity lamp before it is removed from the slide holding fixture.

The finished Ferrogram is evaluated by placing it on the stage of a special microscope. The reflected light source is switched to a controlled D.C. power supply while the photo cell is aligned with the microscope barrel. Using the stage of the microscope the reader is placed at the 55mm position and the Ferrogram is transversed perpendicular to the longitudinal axis to find the highest density. This procedure is repeated at 54.5, 54, 53.5, and 53 millimetres. These readings then are averaged to obtain the optical density value designated as D54. This averaging technique compensates for any variation in the positioning of the delivery tube or the Ferrogram on the microscope stage.

## Experimental Evaluation

With the Ferrographic method, the amount of wear debris is measured directly and these measurements are subsequently used to evaluate the wear process. Hence, it is necessary to evaluate the capabilities and limitation of the Ferrographic technique to accurately measure the amount of wear debris in a fluid sample before using these data to assess a wearing process. In order to accomplish this evaluation a sample was selected from the many pump tests which has been conducted.

Various volumes of liquid from this sample were used in preparing Ferrograms to assess the repeatability and saturation characteristics of the method. The fluid volumes selected were 3, 6, 9, and 12 millilitres and nine Ferrograms were made using each of the selected volumes. This experiment provided information relative to three characteristics which are fundamental to the use of the Ferrographic technique. First of all, the density readings must be repeatable, that is, repeated measurement at the same debris concentration must produce consistent results. Second, since various volumes of sample liquid are used in preparing a suitable Ferrogram, it must be shown that the measurements obtained are linear with volume. This linearity characteristic would permit normalization of the data (e.g., per millilitre). Finally, the saturation tendency of the technique must be known. Figure 6 shows the results of the evaluation of the Ferrographic method using a fluid sample with debris concentration designated as A. From this figure it can be seen that if the D54 density is averaged over the nine Ferrograms made at each volume level, the results are sufficiently linear up to a density value of between 35 and 40. The curved portion of Figure 6 indicates a saturation tendency at close to an optical density of 40 and the decision was made at this point to always obtain a value of less than 40 by proper dilution techniques. In addition, the data scatter observed from these results was greater than desired. The coefficient of variation (standard deviation divide by the mean) (38) (39) (40) (41) for the means of 10.93, 21.69, and 33.29 were 17.89%, 13.64%, and 13.48%, respectively. The 12 millilitre tests had a mean of 38.24 and a coefficient of variation of 6.45%. However, since this is definitely a

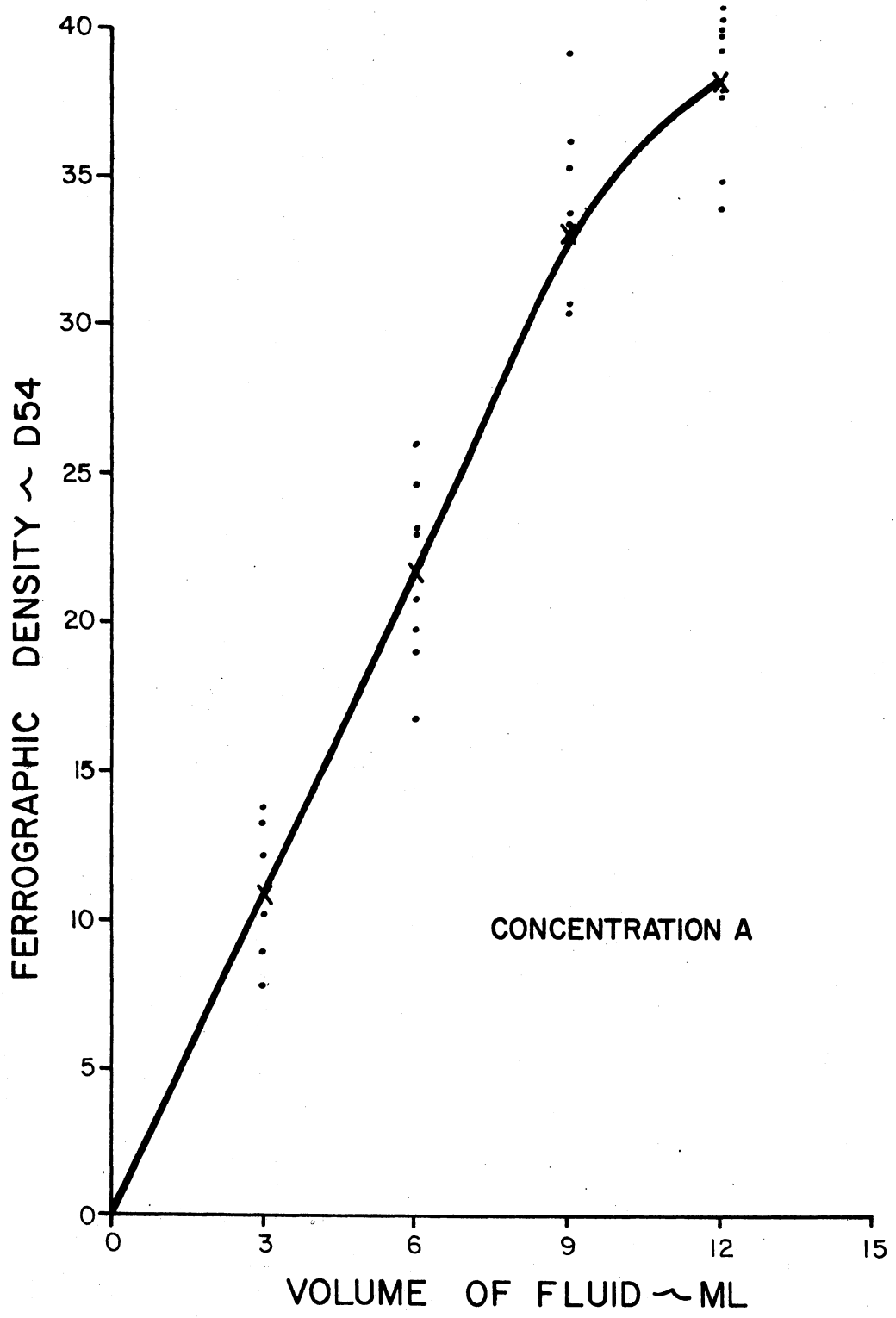


Figure 6. Repeatability and Saturation Characteristics of Ferrographic Method-Initial Procedure

saturated condition, it is not useful in evaluating the variability of the density reading. The increase in the coefficient of variation of the sample data with a mean of 10.93 indicated that the per cent variation increased at low mean values. Therefore, the density values considered acceptable were above a reading of 10. Thus, if the optical density (D54) was below 10 using a given quantity of fluid, the volume was increased until the actual Ferrogram reading at 54mm exceeded 10 but was below 40.

The procedure used in making and evaluating a Ferrogram was studied to determine if the excessive data scatter could be resolved. This investigation revealed three possible sources of variation. The volume measuring devices (eyedroppers) supplied by the equipment manufacturer were not accurately calibrated. This was remedied by procuring precision pipettes for extracting measured amount of the sample liquid. In addition, it was found that the volume flow rate of the tube pump varied probably due to differences in delivery tube dimension as well as viscosity, temperature, etc. Since the preliminary operating procedure dictated by the manufacturer recommended that the pump be operated for a prescribed period of time to produce a certain volume, the difference in flow resulted in volume variations. This problem was overcome by placing a prescribed volume of fluid into the mixing bottle used with the Ferrograph Analyzer. The entire volume in the mixing bottle was pumped across the slide regardless of the time required.

In addition to the variations in fluid volumes, it was found that the power supply which provided a controlled D.C. current to the light source of the densitometer was subject to large variations in voltage. The intensity of the light course would change with the applied voltage

which would be reflected in the output of the photo cell. Therefore the power supply provided by the equipment manufacturer was replaced by a laboratory-type regulated power supply which was adjustable. Using a digital voltmeter to monitor the lamp voltage, the adjustable power supply was used to maintain a constant potential to the lamp.

To assess the improvement brought about by the changes discussed, the experiment was conducted again using a sample with a different concentration of wear debris (Concentration B). The results of this experimental evaluation of the modified Ferrographic technique is shown in Figure 7. It can be noted from the figure that the data scatter has been reduced while the linearity and saturation characteristics are approximately the same. In this experiment a sample which contained a heavier concentration of wear debris was utilized and three Ferrograms were made using liquid volumes of 0.25, 0.50, 0.75, 1, 2, and 3 millilitres. The reading obtained at 2 and 3 millilitres were far beyond saturation limits. The mean D54 reading obtained were 13,07, 24.3, 33.13, 39.2, 62.6, and 80.5 in order of increasing volumes. The coefficient of variation for these mean D54 values (using the range to estimate the standard deviation (42) were 7.69%, 4.86%, 4.82%, 6.78%, 1.98%, and 0.62%. From these data, it was concluded that the data scatter due to the Ferrographic process had been reduced by about 50%.

Further appraisal of the Ferrographic technique led to the conclusion that additional improvements in the process would require some redesign of the hardware. For example, it is felt that the variations in the flow across the slide will result in different density readings.

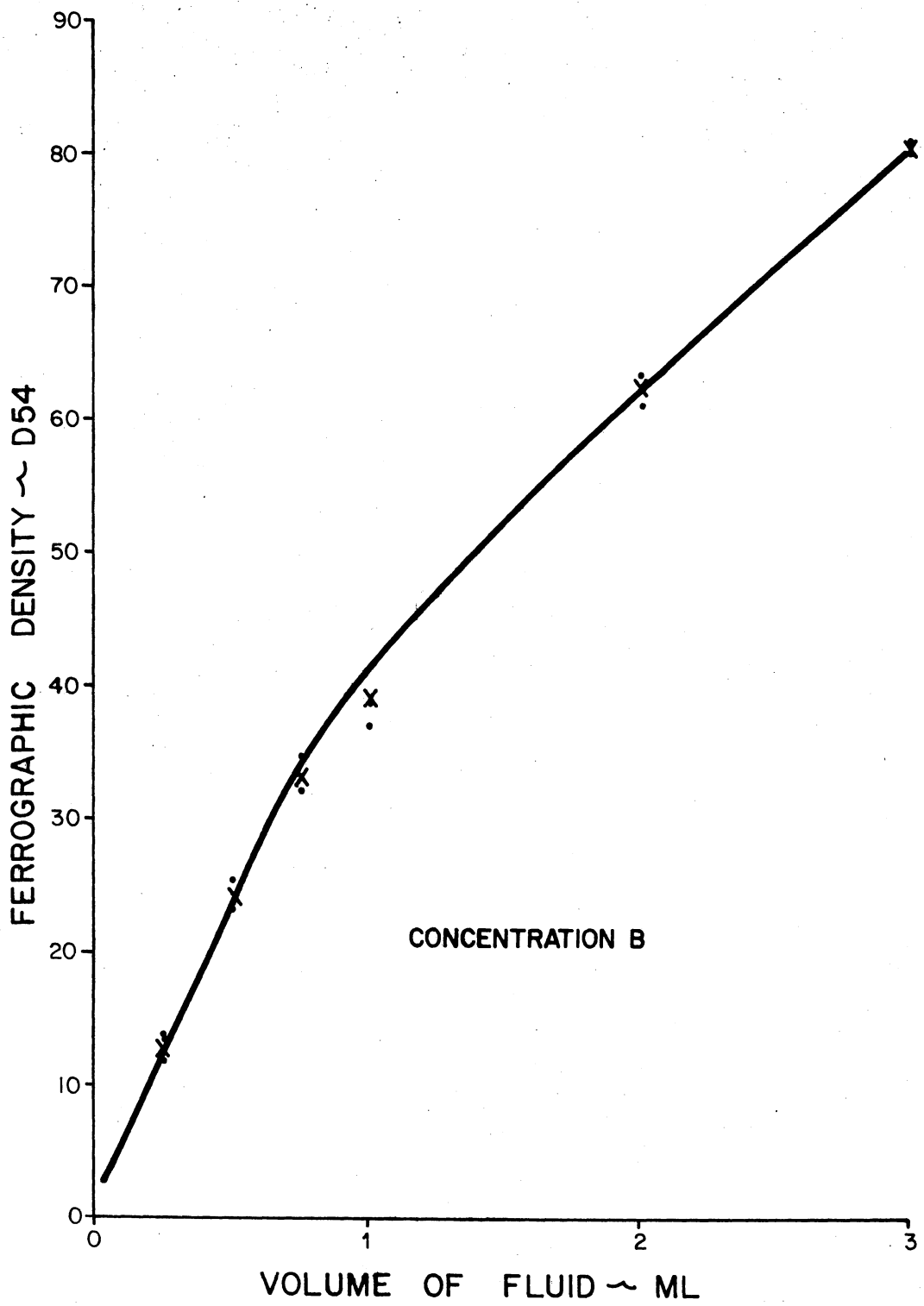


Figure 7. Repeatability and Saturation Characteristics of Ferrographic Technique-Modified Procedure

Since the liquid stream is contained on either side by the special boundary film any change in flow will be reflected by an increase or decrease in the height of the stream. Thus, wear particles initially situated at the top of the fluid stream would have a different distance of travel before encountering the substrate. In addition, at higher flows the drag forces on each particle would be increased and therefore the particle would be located further along the substrate. However, in order to make the flow rate adjustable, a new feed mechanism would have to be developed and verified. Such an endeavor was considered beyond the scope of this research effort.

In order to utilize the Ferrographic density readings in the evaluation of contaminant wear in a gear pump, it was necessary to develop a wear model. From the hypothesis, that the primary effect of the contaminant wear process is to increase the clearance within the pump, relationship must be derived which relate Ferrographic density to the overall clearance change and this clearance change must be expressed in terms of flow degradation. The rationale and assumptions used in the development of a Ferrographic Wear Model for a gear pump is discussed in the next chapter.

# CHAPTER IV

## ANALYSIS OF CONTAMINANT WEAR USING FERROGRAPHIC DATA

The role of a pump in a hydraulic system is to deliver liquid to the other system components at a rate proportional to the speed of the pump. When this capability is no longer satisfactory the pump is said to be worn out. As shown in the flow chart of Figure 8, when a pump operating in a system at some set of conditions (pressure, speed, temperature, etc.) is exposed to entrained contamination the critical surfaces within the pump are abraded. The destruction of these surfaces will result in the enlargement of clearances within the pump and the generation of wear debris. Through the use of the Ferrographic technique, the amount of wear debris generated during a given contaminant exposure can be measured; however, the associated effective clearance change is impossible to measure in modern fluid power pumps.

The primary result of the increase in clearance (increased leakage of flow degradation) can be measured. The contaminant sensitivity of a gear pump could be evaluated from either flow degradation or wear debris data. However, the function of a hydraulic pump is not to generate wear debris but to produce flow. Therefore, to be ultimately useful it is necessary to evaluate the degree of contaminant wear in a hydraulic pump in terms of flow degradation. The problem which exists in evaluating the contaminant sensitivity of a pump directly from flow loss measurements

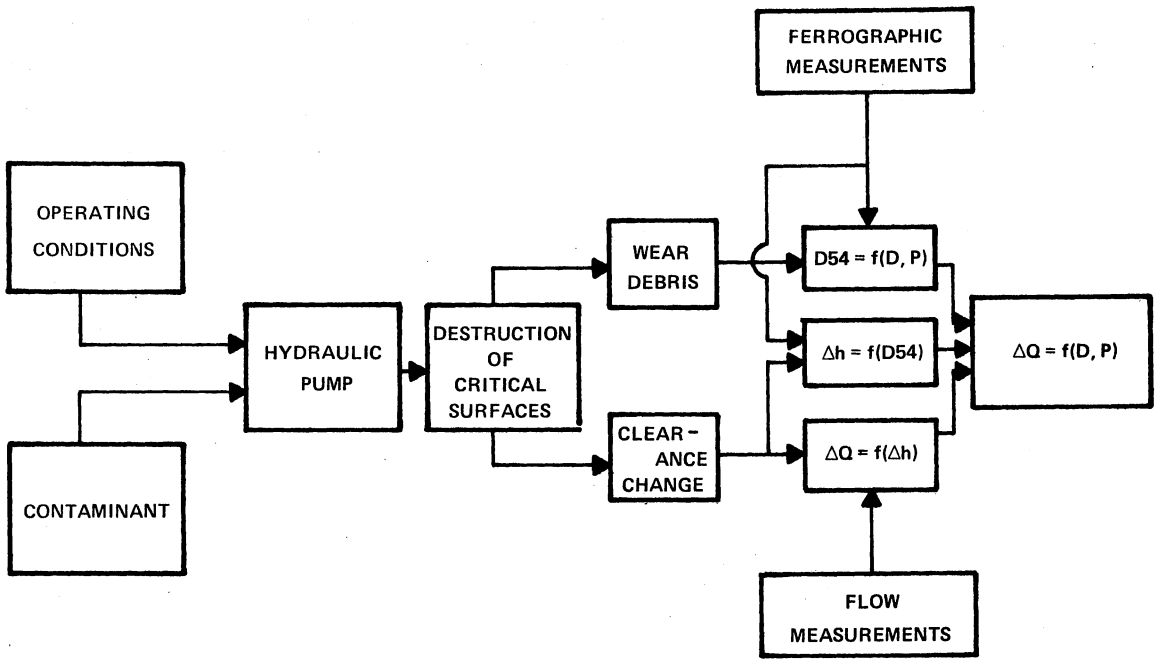


Figure 8. Flow Chart for Contaminant Wear in Hydraulic Pumps

lies in the magnitude of this parameter resulting from low contamination. That is, in order to produce adequate flow degradation for accurate measurement it is necessary to accelerate the contaminant wear process by using an excessive contaminant concentration (300 mg/$\ell$ in the standard test).

As discussed in Chapter II, previous investigations have evaluated the contaminant wear in a pump through the use of only flow degradation. This work has led to the development of a log-normal model as shown in Figure 4 for the performance degradation (flow loss) of hydraulic pumps. While this type of analysis produces useful data for interpretation of pump contaminant sensitivity, it requires an extremely high contaminant concentration. Reducing the contaminant concentration results in very small flow degradation which can not be accurately measured.

Wear debris measurements through Ferrographic analysis offers a new method for assessing the contaminant sensitivity of a hydraulic pump. A functional relationship was presented in Chapter II connecting the amount of wear debris generated with the particle size distribution of the entrained contaminant exposed to a pump and the outlet pressure imposed. In order to use this relationship in expressing the contaminant wear of a pump in terms of flow degradation, two more expressions are needed. One of these equations can be developed by modeling the leakage paths of a pump on a lumped basis where the changes in clearances within the pump are represented by an increase in an equivalent clearance. The other expression is a coupling equation which relates the wear debris generation in terms of the change in this equivalent clearance.

The remainder of this Chapter will analyze the contaminant wear process in a gear pump to develop the form of the necessary wear model.

The Ferrographic measurement and flow evaluation during a pump contaminant wear test are independent and thus can both be used in identifying the parameters of a wear model. The next section of this chapter will investigate the flow degradation relationships which governs the contaminant wear process. Then a section will be devoted to the expressions which describe the generation of wear debris. The last section of this chapter will consider the coupling relationship which completes the Ferrographic Wear Model. From Figure 8 the Ferrographic Wear Model can be expressed in a general form as follows:

$$\begin{aligned} D54 &= f_1(D,P) \\ \Delta h &= f_2(D54) \\ \Delta Q &= f_3(\Delta h) \end{aligned} \qquad (2)$$

where:

D54 = Ferrographic density measured at the 54mm position

D = particle size

P = pump outlet pressure

$\Delta Q$ = pump incremental flow loss

$\Delta h$ = equivalent clearance change

## Flow Degradation Due to Contaminant Wear

In general, there are three critical leakage paths inherent to hydraulic gear pumps (22) (43) (44) (45) (46). One path is defined by the clearance between the tip of the gear teeth and the internal wall of the housing. A second path is across the side face of the gears to the pump bearings. Flow between this latter surface and the loading plate of the pump is used to lubricate the bearing and is relieved back to the

suction of the pump. The third path is also defined by the gear faces and the loading plate but is located at the meshing area of the gears and permits the leakage to flow directly back to the suction cavity of the pump. It should be noted that each of these leakage paths is subjected to a pressure differential and each is characterized by one moving boundary. Since these leakage paths are complex and act together to form the total leakage flow of the pump, rigorous modeling was not attempted. The objective in the following discussion is to obtain a simplified model form which is guided by experimental data from the pump.

The general expression normally used (43) (44) (45) (46) for describing the output flow of a gear pump can be written as follows:

$$Q_o = f(D_P, h, \Delta P, N, \mu, T) \qquad (3)$$

where:

$Q_o$ = output flow of pump

$D_P$ = pump displacement

$h$ = characteristic clearance

$\Delta P$ = pressure drop

$N$ = speed

$\mu$ = viscosity

$T$ = temperature

In order to determine a more explicit form of Equation (3), five gear pumps were evaluated at various pressures and speeds while maintaining viscosity and temperature constant. Since the results on all five pumps (given in Appendix A) were quite similar the data of only two of these tests as shown in Figuree 9 and 10 will be used. The five

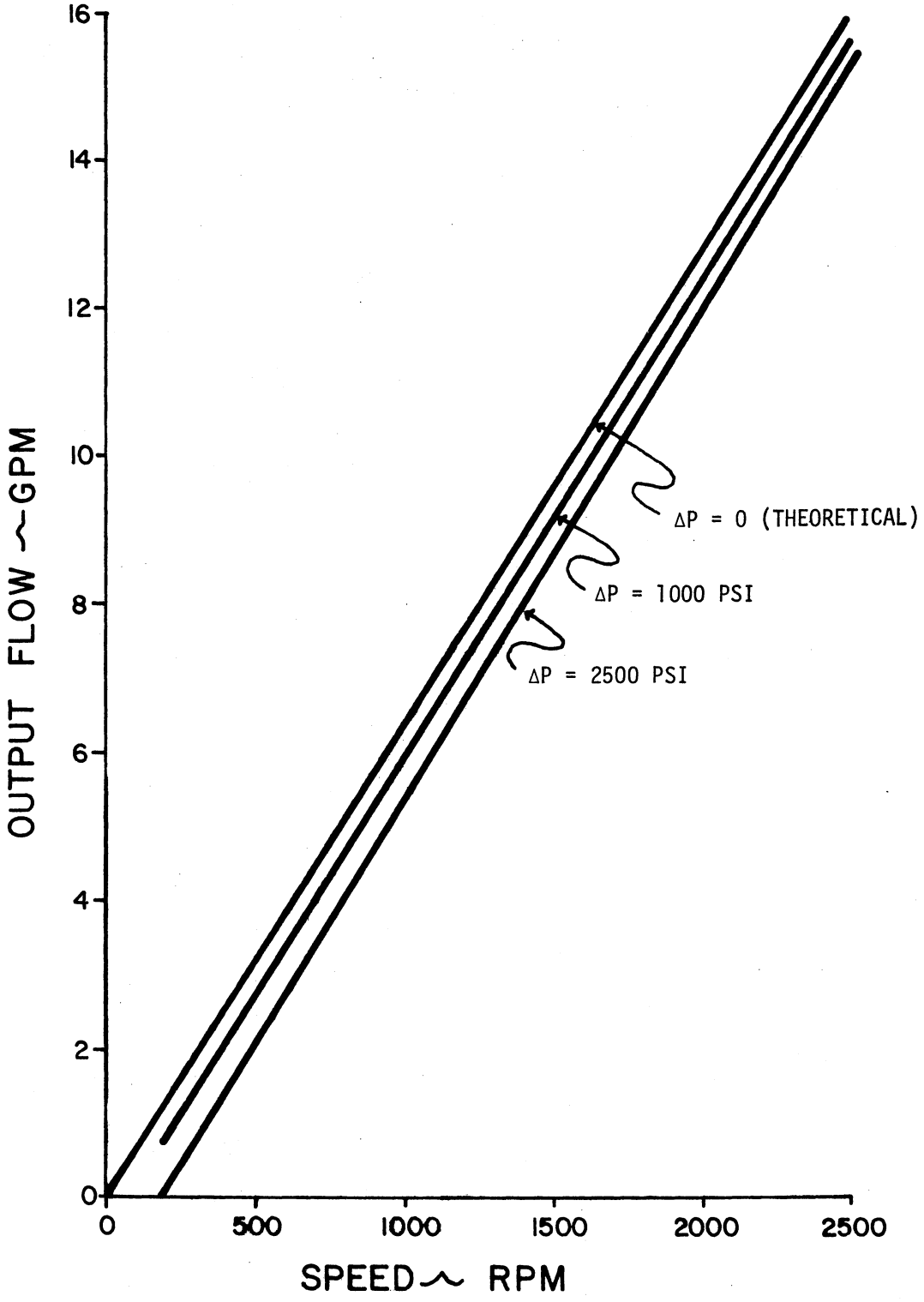


Figure 9. Results of Performance Test on Pump 302

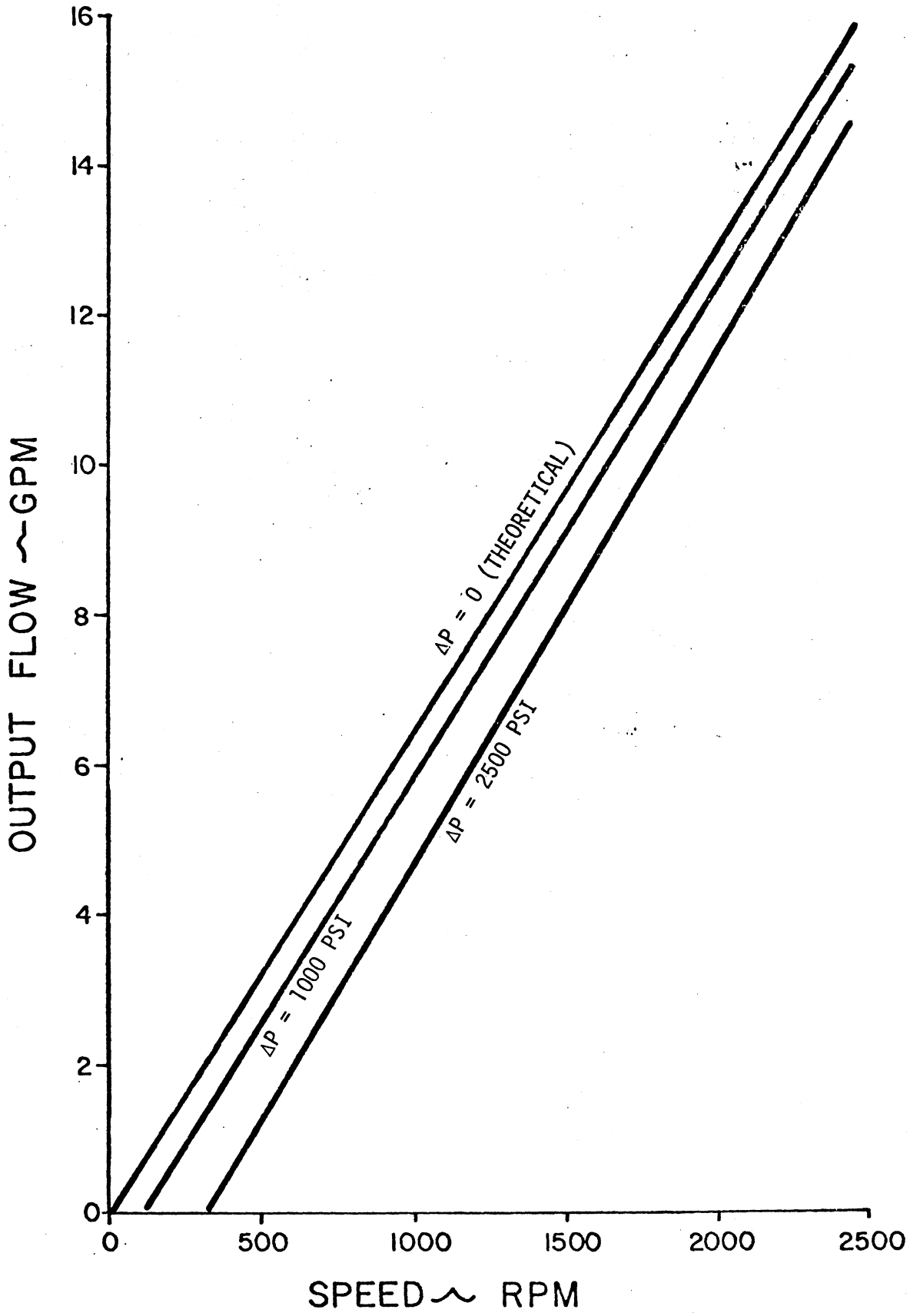


Figure 10. Results of Performance Test on Pump 303

pumps tested were randomly selected from a lot of 12 pumps which were reported to be "identical" by the manufacturer. In all of these tests output flow was measured using a calibrated turbine-type flow meter at speeds increasing by 100 RPM starting at 1000 RPM and continuing to 2500 RPM. Pressures of 500, 1000, 1500, 2000 and 2500 psi were selected for use in these tests. The purpose of these tests was to develop the form of the flow model.

It can be noted in Figures 9 and 10 that the output flow of the pump decreases with pressure and increases with speed. The theoretical curve ($\Delta P=0$) was found by extrapolating the pressure data. Of particular interest from these curves is the fact that the best fit straight line (by the method of least squares) (47) for the various pressures does not indicate a constant slope. This implies that either there is a change in the effective displacement of the pump at various pressures or the leakage of the pump is a function of pump speed. For example, the leakage of the pumps used in Figures 9 and 10 can be found for a given speed from the following expression:

$$Q_\ell = Q_o\Big|_{\Delta P=0} - Q_o\Big|_{\Delta P=P} \tag{4}$$

Using the equation obtained by the least squares curve fit of the data, the leakage at 1000 and 2500 psi are shown in Figures 11 and 12 for pumps 302 and 303 respectively as a function of pump speed.

The curves shown in Figures 9, 10, 11 and 12 indicate that the expression for the output flow of the gear pumps tested here should be of the form:

$$Q_o = Q_t - Q_\ell \tag{5}$$

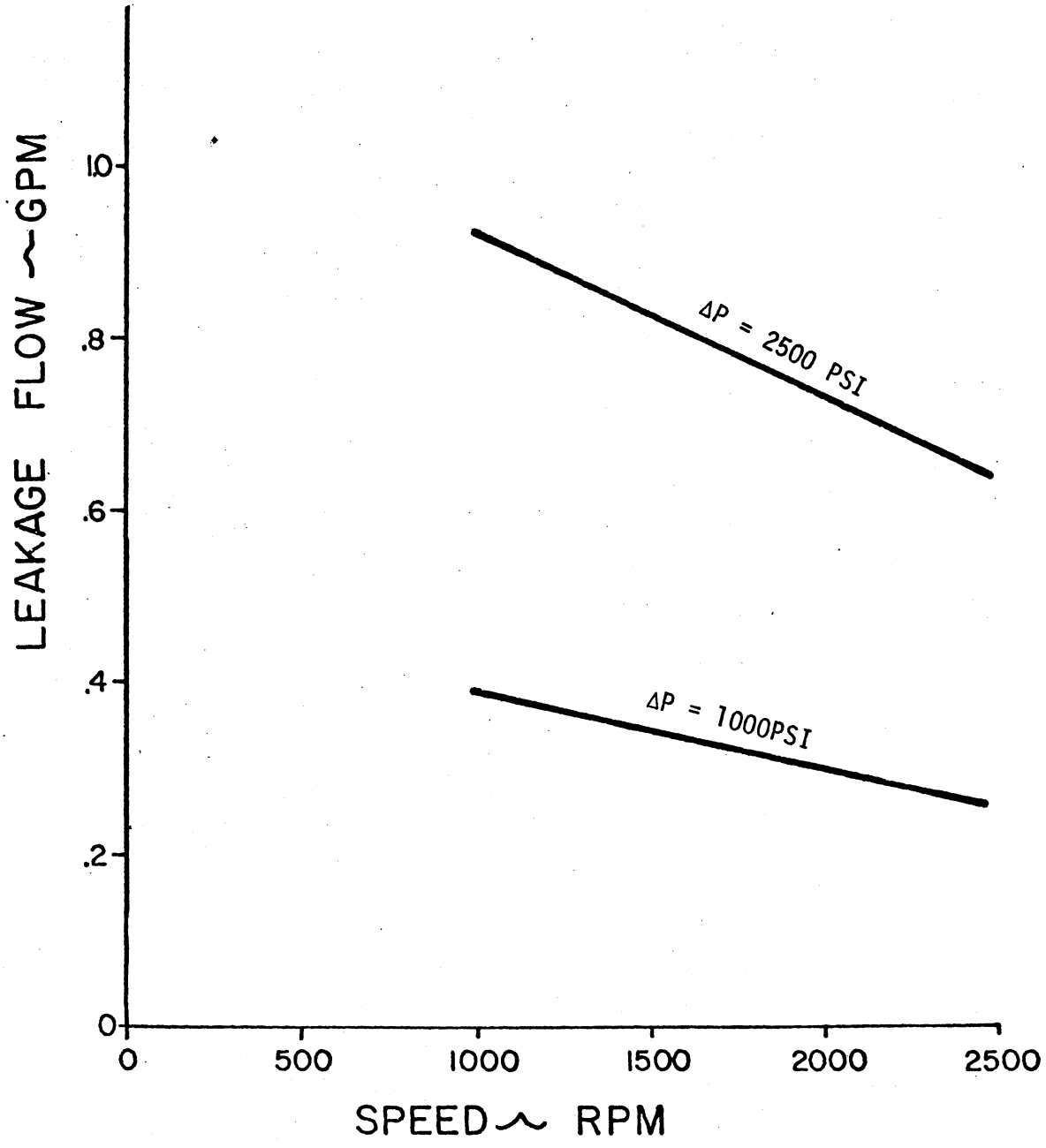


Figure 11. Leakage Flow as a Function of Speed at Various Pressures for Pump 302

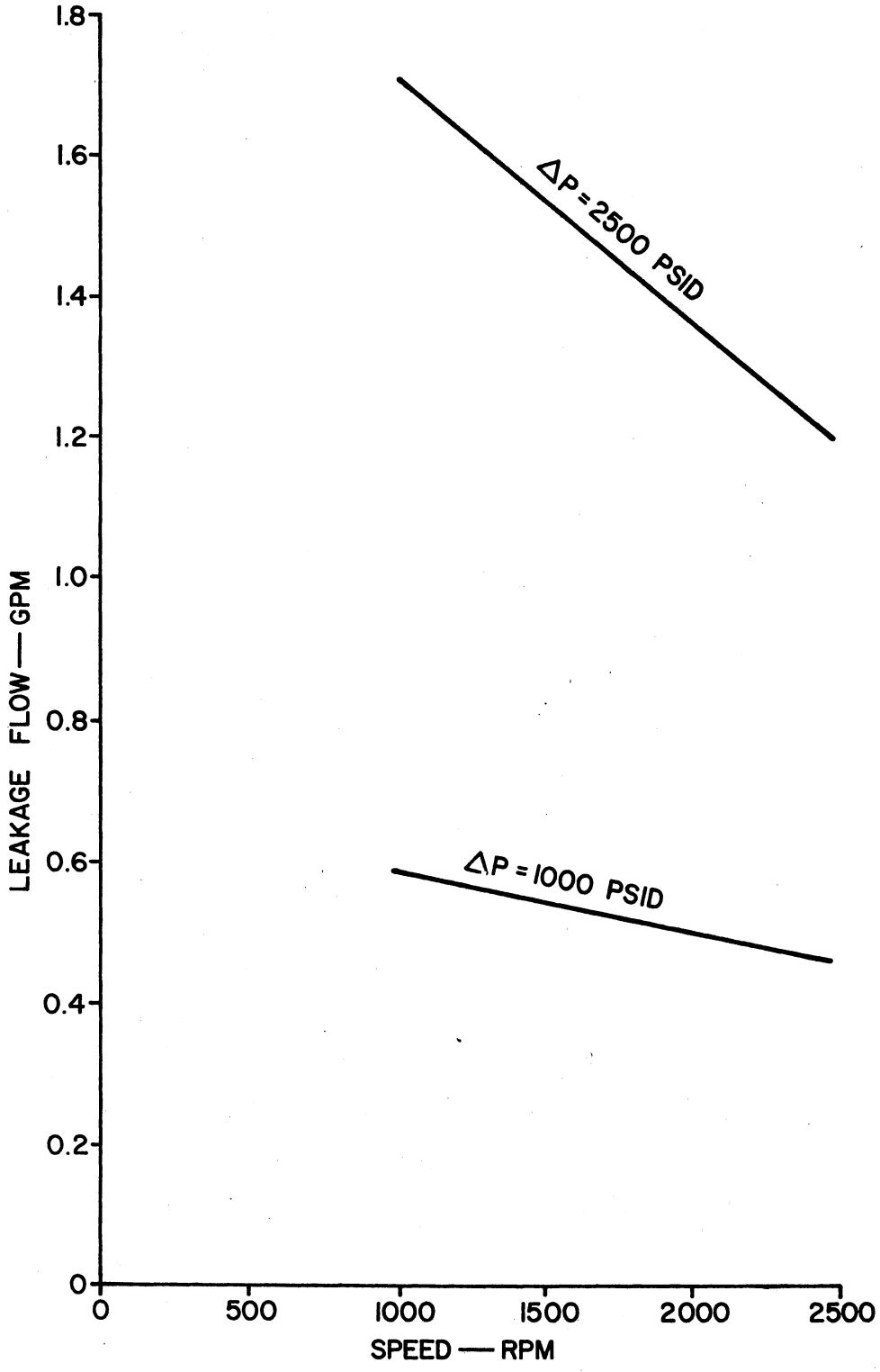


Figure 12. Leakage Flow as a Function of Speed at Various Pressures for Pump 303

where:

$Q_t$ = theoretical flow

$Q_\ell$ = leakage flow

The theoretical flow, $Q_t$, is defined as the output flow with a zero pressure differential across the pump and can be written as follows:

$$Q_t = KD_PN \tag{6}$$

where:

K = proportionality constant

$D_P$ = displacement found at zero pressure differential

The leakage flow, $Q_\ell$, is obviously a function of both speed and pressure. Furthermore, this quantity is a linear function of these two parameters. Therefore, the expression for the leakage flow can be written as follows:

$$Q_\ell = K_1\Delta P - K_2N \tag{7}$$

where:

$K_1$ and $K_2$ = constants of proportionality

As might be expected, the form of Equation (7) suggests that flow in the leakage paths of gear pump adheres to the hydrodynamic lubrication theory for viscous flow between parallel surfaces, one fixed and one moving (43) (44) (45) (46). This theory states that $K_1$ is a function of the clearance between the surfaces to the third power and other parameters such as length and width of the flow passage and the viscosity of the flowing liquid. In addition, the theory states that $K_2$ is proportional to the clearance divided by 2 which accounts for a linear velocity distribution across the flow passage. Since the parallel plate arrangement displays the same flow behavior as the pump model depicted in Equation (7), the

distance between the two parallel surfaces can be treated as the equivalent clearance of the pump.

Since the objective of this modeling exercise is to formulate a model which can be used to relate flow degradation to the equivalent clearance changes, all other variables effecting leakage flow need not be explicitly depicted. Consequently, the leakage expression, Equation (7), can be rewritten to explicitly show the dependence of leakage flow upon the equivalent clearance as follows:

$$Q_\ell = K_3 h^3 \Delta P - K_4 h N \tag{8}$$

where:

$K_3$ and $K_4$ = constants of the pump

h = equivalent clearance representing the composite leakage paths

Substituting Equations (6) and (8) into Equation (5) and rearranging yields the following relationship.

$$Q_o = KD_P N + K_4 h N - K_3 h^3 \Delta P \tag{9}$$

Equation (9) is sufficiently well defined for the development of an expression for use in contaminant wear evaluation, since such wear tests are conducted at constant speeds and pressures.

In a contaminant sensitivity test the pump is subjected to a given size range and concentration of AC Fine Test Dust. Damage to the pump results in an increase in the effective clearance represented by h in Equation (9). Therefore, the flow of the pump after the first exposure can be written as follows:

$$Q_{of} = KD_P N + K_4 (h+\Delta h) N - K_3 (h+\Delta h)^3 \Delta P \tag{10}$$

where:

$Q_{of}$ = output flow after contaminant exposure

$\Delta h$ = change in the equivalent clearance of the pump due to contaminant wear

The flow degradation, therefore, can be found by subtracting Equation (10) from Equation (9). Performing this manipulation and simplifying produces the following relationship:

$$\Delta Q = (3K_3h^2\Delta P - K_4N)\Delta h + (3K_3h\Delta P)\Delta h^2 + (K_3\Delta P)\Delta h^3 \quad (11)$$

where:

$\Delta Q$ = flow degradation due to contaminant wear

Since it would be impossible to quantify each of the variables of Equation (11), for a given pressure drop, speed, an initial value of clearance it can be further reduced as follows:

$$\Delta Q = C_1\Delta h + C_2\Delta h^2 + C_3\Delta h^3 \quad (12)$$

The expression given by Equation (12) represents the transformation needed to relate the wear caused by contamination (i.e., $\Delta h$) to the resulting flow degradation. Unfortunately, there is no way of non-intrusively measuring the independent variable, $\Delta h$, of this relationship directly. Therefore, this variable must be evaluated indirectly which is the purpose of the wear debris analysis technique.

## Debris Generation From A Gear Pump

Any wear process which results in a destruction of a material surface produces debris. If during the wear of a flow path only one dimension is altered then the amount of wear debris generated will be directly proportional to the dimensional change of the path. It is

extremely difficult to visualize and illustrate the leakage paths of a gear pump although they can be adequately described. For descriptive purposes it will be assumed that each of the three critical leakage paths are rectangular.

Consider, first, the leakage path defined by the sides of the gears and the surface of the loading or wear plate as it is commonly called. Fluid which enters this space must either flow to the bearing cavities or across the meshing area of the gears directly to suction. The liquid flow to the bearing cavities is indicated as $Q_1$ in Figure 13 which shows the cross-section of a gear pump in schematic form. The leakage which crosses the meshing area of the teeth is called $Q_2$ in Figure 13. The length of the path in which $Q_1$ flows is determined the root diameter of the gear teeth and the hole in the wear plate through which the pump shaft passes. The width of the $Q_1$ path is the mean arc length between the root diameter of the gear and the diameter of the shaft. On the other hand, the length and width of the path through the gear mesh area are controlled by the length and width of the gear teeth. In neither of these two paths is contaminant wear likely to alter the length or width of the leakage paths to any appreciable degree. The clearance of both paths is the distance between the gear faces and the surface of the wear plate and this is the dimension which is altered during contaminant wear. It is logical to conclude therefore that material removed from the gear faces or wear plate surface will be directly reflected in the clearance change between them.

The leakage path defined by the tip of the gear teeth and the body of the pump has a length proportional to the distance across the gear tip. The width of this leakage path is equal to the width of the gear.

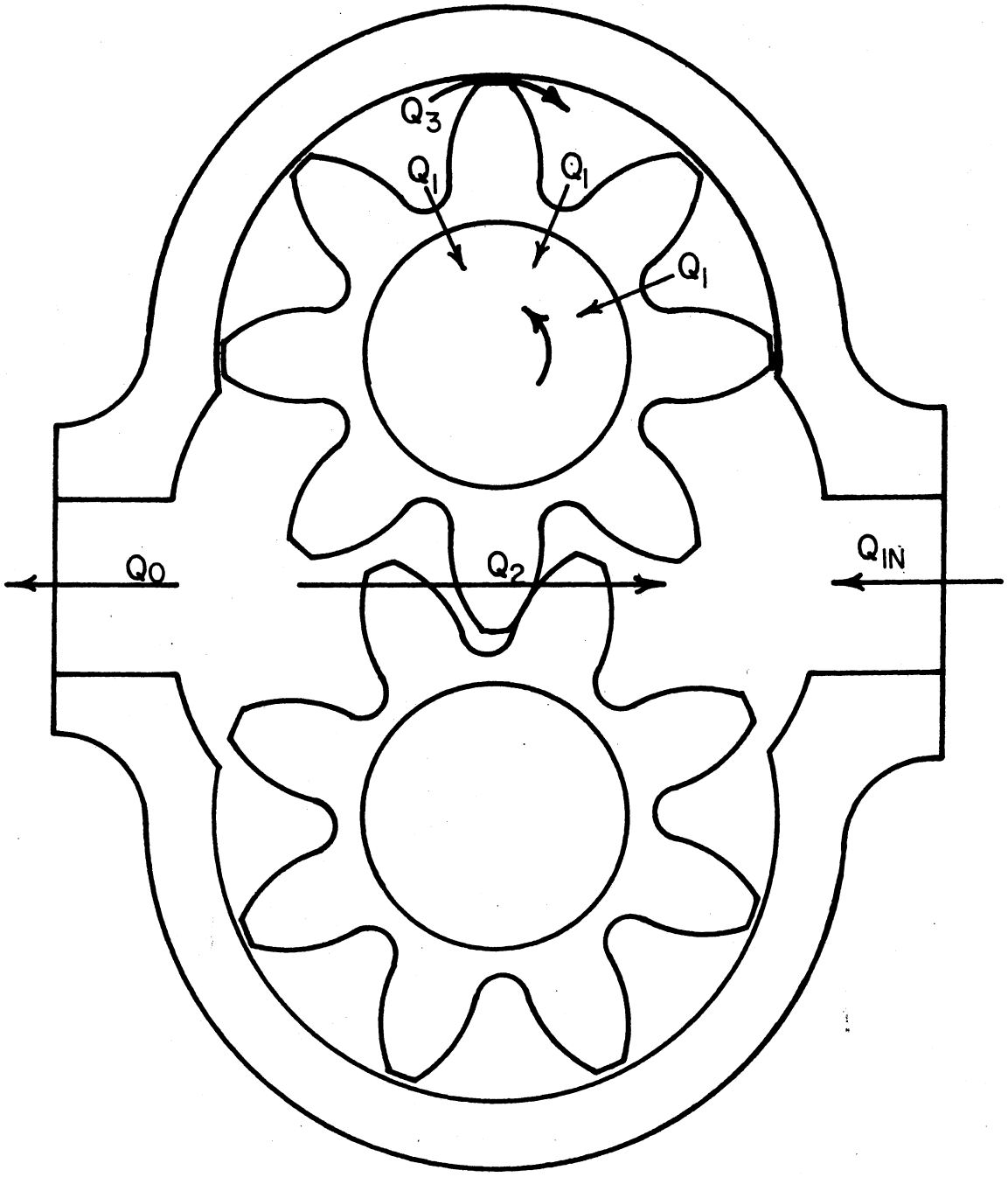


Figure 13. Schematic Cross-Section of a Gear Pump

Here again, it is not conceivable that wear due to entrained contamination would alter the length or width of this leakage path. The height of the leakage path is defined by the clearance between the gear tips and the internal surface of the pump body. Contaminant wear could easily alter this dimension. Thus the amount of wear debris generated due to a contaminant attack should be proportional to only the clearance change for each of the three major leakage paths in a gear pump. Assuming that the net change in these clearances can be represented by a change in the equivalent clearance of the pump, the volume of wear debris removed during contaminant exposure becomes:

$$V = wL\Delta h \tag{13}$$

where:

V = volume of wear debris generated

w = width of leakage path

L = length of leakage path

$\Delta h$ = change or increase in equivalent clearance of the pump

From the published results of previous research efforts by Rabinowicz and others (14) (16) shown in Figure 1, it can be assumed that the volume of wear debris generated would be a power function of the particle size range of the contaminant exposed to the pump. This relationship can be expressed as follows:

$$V = aD^b \tag{14}$$

where:

a = constant coefficient

D = particle size of the contaminant

b = constant proportional to the loading conditions which exist between the two wearing surfaces

Equation (14) and Equation (13) can be combined to produce the following equation:

$$\Delta h = \frac{a}{wL} D^b \tag{15}$$

Finally Equation (15) can be substituted into Equation (12) to yield an expression for the flow degradation in terms of the particle size distribution and concentration of the contaminant to which the pump was exposed as follows:

$$\Delta Q = C_1\left(\frac{a}{wL}\right) D^b + C_2\left(\frac{a}{wL}\right)^2 D^{2b} + C_3\left(\frac{a}{wL}\right)^3 D^{3b} \tag{16}$$

To utilize this equation, the constants must be identified from experimental data. If a low contaminant concentration is used (below 300 mg/$\ell$) there would be very little flow degradation making the identification procedure difficult and of dubious accuracy. However, by measuring the amount of wear debris through Ferrographic techniques the constants a/wL and b can be evaluated leaving only $C_1$, $C_2$, and $C_3$ to rely upon flow degradation data.

## Ferrographic Density and Debris Concentration

The Ferrographic technique is actually a means of separating the wear debris present in an oil sample from both the vehicle fluid and extraneous material. From the results reported during the development and verification of the technique (documented in the various references) it is logical to conclude that the amount of debris deposited upon the Ferrogram would be proportional to the concentration of the wear debris in the sample fluid. Furthermore, research work conducted by the author has revealed that the optical density measured at the 54 mm location on

the Ferrogram (D54) is the most responsive to the contaminant wear debris. This leads to the development of the following expression.

$$V = C_4(D54) \tag{17}$$

where:

$C_4$ = a constant of the Ferrographic process

D54 = optical density measured at the 54 mm location on a Ferrogram

By substituting Equation (17) into Equation (14) the following expression is produced

$$D54 = \frac{a}{C_4} D^b \tag{18}$$

Since various amounts of sample fluid can be used in obtaining the density value even a very slight amount of debris can be accurately assessed. That is, if the contaminant wear process produced a flow change which was too small to measure practically, a very small amount of wear debris would be generated. However, by passing a large amount of sample fluid across the substrate a sufficient quantity of wear debris will be deposited to permit accurate evaluation if the limitations of the Ferrographic technique are adequately respected.

## Ferrographic Wear Model

From the preceding development an expression for the flow degradation in terms of the equivalent clearance change, Equation (12), and a relationship for the Ferrographic density as a function of contaminant exposure, Equation (18), have been advanced. However, as they now stand these two equations are independent and, in fact, the equivalent clearance change used in Equation (12) can not be measured. Therefore,

to complete the Ferrographic Wear Model an expression must be found which couples the two describing equations. By examining Equations (13) and (17), it can be seen that both the equivalent clearance change, $\Delta h$, and the Ferrographic density, D54, are linearly related to the volume of debris generated. This relationship can be expressed as follows:

$$\Delta h = K_5(D54) \tag{19}$$

The Ferrographic Wear Model, then, consists of Equations (18), (19), and (12) and can be written as follows:

$$\begin{aligned} D54 &= a_1 D^b \\ \Delta h &= K_5(D54) \\ \Delta Q &= C_1\Delta h + C_2\Delta h^2 + C_3\Delta h^3 \end{aligned} \tag{20}$$

It should be noted that the three expressions comprising the Ferrographic Wear Model could be combined to produce only one equation. However, the results of such a combination would obscure the true meaning of the model and preclude the use of both measurements, (D54 and $\Delta Q$) in identifying the individual parameters of the Ferrographic Wear Model.

To use this model a contaminant sensitivity test would need to be conducted on the gear pump. A fluid sample would be extracted at the conclusion of each contaminant exposure. However, the contaminant concentration could be greatly reduced from the 300 mg/$\ell$ presently used since the Ferrographic analysis is much more sensitive to small changes in clearance than is flow changes. Since a density reading will be obtained at each contaminant exposure regardless of whether or not the flow change is measurable, several data points can be obtained to identify the constants of the first equation in the model without

excessive degradation in flow. The successive exposures (0-5, 0-10, 0-20, etc.) need only be continued until a measurable flow degradation has occurred after two exposures. This will produce sufficient data for the identification of the constant in the last expression of the model. Since very little damage has been done to the pump during this test, a new test can be conducted on the same pump operating at a different set of operating conditions (e.g., a different pressure).

An extensive testing program was conducted to verify the relationships which have been developed. In all 24 pump tests were conducted, not counting the experiments to evaluate the performance characteristics of the test pumps. These tests were run at various contaminant concentrations, pressure, speed, and sequence. The sequence tests were made to determine the significance of running a gear pump more than once to evaluate the contaminant wear characteristics at different operating conditions. The results of these tests are presented in the following chapter.

# CHAPTER V

## EXPERIMENTAL VERIFICATION OF FERROGRAPHIC WEAR MODEL

There are numerous parameters of almost any hydraulic component which can not be measured directly. For example, most hydraulic gear pumps used today are termed either pressure loaded or wear compensated. This means that such pumps include a plate which is balanced against the sides of the gears by hydrostatic and hydrodynamic forces. Therefore, it is not possible to accurately measure the clearance of any of the critical leakage paths within a gear pump. Thus, in order to verify the model developed in Chapter IV it was necessary to conduct tests in which both the flow degradation and the Ferrographic data were obtained. The degree of correlation between these two sets of data will provide the verification of the Ferrographic Wear Model.

To accomplish the testing phase of this effort 12 gear pumps were obtained from a single manufacturer. These pumps were from the same manufacturing lot and carried identical part numbers. However, as can be seen from the performance data presented in Chapter IV and Appendix A, there was considerable variation in the initial volumetric efficiency of the pumps. This variation was not expected to cause any problem in this effort because the results are primarily concerned with change in performance (flow) and not total volumetric efficiency.

## Experimental Methods

The 12 pumps were first randomly numbered commencing with 300 and concluding at 311. The test plan followed is shown in Figure 14. As can be seen from this plan speeds of 1500, 2000, and 2500 RPM and pressures of 1500, 2000, and 2500 psid were selected. These ranges covered the normal spectrum of operating conditions used for gear pumps. The contaminant concentration levels used as shown in Figure 14 were 10, 20, 25, 75, 150 and 300 milligrams per litre. While not shown in this figure the particle size ranges used were 0-5, 0-10, 0-20, 0-30, 0-40, 0-50, 0-60, 0-70, and 0-80 micrometres obtained by classification using air elutriation from AC Fine Test Dust (48).

The equipment utilized for conducting these tests is shown pictorially in Appendix B. Briefly the test stand consisted of a 100 hp constant speed motor which drove the pumps through a belt and pulley arrangement. Various sized pulleys were used to obtain the different test speeds. The pressure at the output of the pump was measured by a calibrated bourdon type pressure gage and maintained through the use of a needle valve placed in the flowing circuit. The test circuit is shown schematically in Figure 15. Heat exchangers utilizing cool water provided adequate temperature control while temperature measurement was accomplished through the use of a gas filled monitoring system. A highly efficient filtering sub-system which could be valved into the main circuit was utilized to remove both the contaminant and wear debris after each exposure. The output flow of the test pump was monitored by a calibrated turbine type flow meter.

| SPEED (RPM) | PRESSURE (PSID) | CONT. LEVEL MG/ℓ | PUMP NUMBER |
|---|---|---|---|
| 1500 | 1500 | 20 | 307-1 |
| | 2000 | 20 | 305-2 |
| | 2500 | 20 | 307-2 |
| 2000 | 1500 | 20 | 300-5 |
| | | 20 | 306-1 |
| | | 20 | 308-2 |
| | | 150 | 304 |
| | 2000 | 0 | 300-1 |
| | | 10 | 300-2 |
| | | 20 | 300-3 |
| | | 20 | 306-2 |
| | | 20 | 308-3 |
| | | 25 | 302-1 |
| | | 75 | 309 |
| | | 150 | 301 |
| | | 300 | 310 |
| | | 300 | 311 |
| | 2500 | 20 | 300-4 |
| | | 20 | 306-3 |
| | | 20 | 308-1 |
| | | 150 | 303 |
| 2500 | 1500 | 20 | 305-3 |
| | 2000 | 20 | 307-3 |
| | 2500 | 20 | 305-1 |

Figure 14. Experiment Test Plan

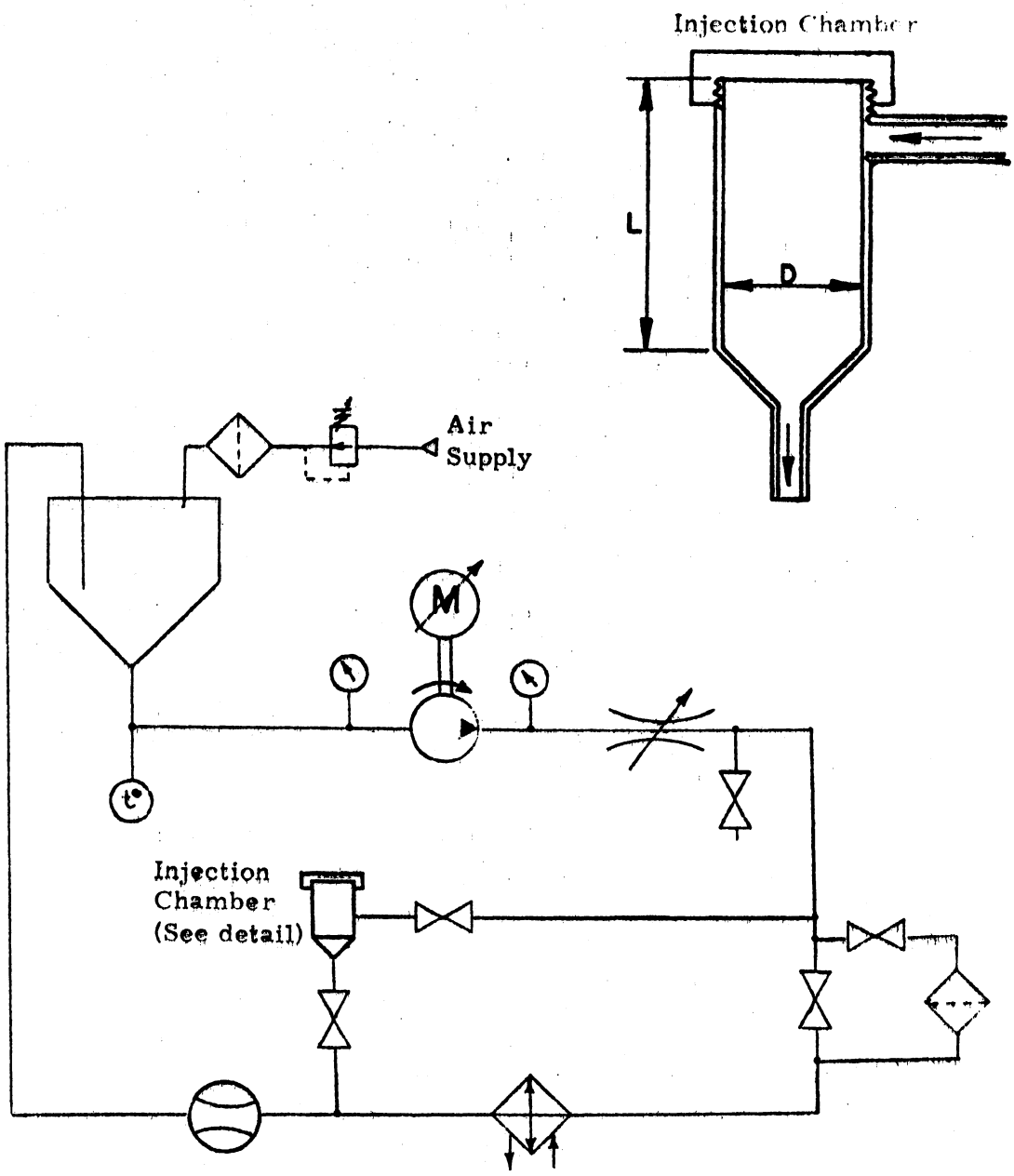


Figure 15. Schematic of Test Circuit

The test procedure followed is outlined in Appendix C. Basically, the standard contaminant sensitivity test (49) was used with the exception of the contaminant concentrations which were selected. The test pumps were all subjected to a break-in period consisting of operating the pump sequentially at 2500 RPM, and 625 psid, 2500 RPM and 1250 psid, 2500 RPM and 1875 psid, and then at 2500 RPM and 2500 psi until the measured output flow remained constant for a period of one hour. Then five of the pumps were tested at various pressures and speed to evaluate the performance characteristic. The performance data is included in Appendix A. The performance tests did not damage the pumps so they were also used for contaminant wear tests.

In the wear tests the pump was operated at the desired conditions of speed and pressure until the temperature stabilized at 150$^{\circ}$F. The initial flow rate of the pump was accurately measured and then the pump was exposed to the required concentration of contaminant in the 0-5 micrometre size range. The pump was operated with this entrained contamination level until the flow remained constant for 10 minutes or until 30 minutes had elapsed. At this point a fluid sample was extracted from the system for Ferrographic analysis and the control filters were valved into the main test system. The filtering period was 10 minutes after which an accurate flow measurement was made. The filtering subsystem was removed from the test system and the 0-10 micrometre size range was injected. This procedure was repeated for 0-20, 0-30, 0-40, 0-50, 0-60, 0-70, and 0-80 micrometre particle size ranges sequentially.

## Test Results

The flow degradation data obtained during the contaminant wear tests are included in Appendix D while the Ferrographic results are shown in Appendix E. Before using the test data to evaluate the Ferrographic wear model, it was subjected to various statistical analyses to determine which of the various test variables had a significant influence on the test outcome. The test plan was arranged to provide a latin square statistical sub-plan which could be effectively used to evaluate the influence of conducting more than one test on a given pump. In addition, a factorially arranged sub-plan was included to be used in appraising the significance of both speed and pressure. Furthermore, a series of tests were conducted at constant speed and pressure (2000 RPM and 2000 psid) to evaluate the influence of concentration and to select the minimum level at which realistic results could be obtained. The latin square arrangement is shown in Figure 16 while the factorial arrangement is illustrated in Figure 17.

The objective in arranging the experimental tests in this manner was, of course, to evaluate the effect of these various variables, but it should be recognized that if the statistical tests reveals no significant influence from any of the variables, the data can be averaged to provide a stronger test base. For example, if the standard analysis of variance reveals that the sequence of testing has no significant effect, then the results of tests on pumps 300, 306, and 308 can be appropriately averaged to obtain a better estimate of the influence of other variables such as speed and pressure.

The statistical analysis of the latin square arranged tests revealed that the sequence of testing did not have a significant influence on

| SEQUENCE | | | |
|---|---|---|---|
| PRESSURE (PSID) | TEST NO 1 | TEST NO 2 | TEST NO 3 |
| 1500 | 306 | 308 | 300 |
| 2000 | 300 | 306 | 308 |
| 2500 | 308 | 300 | 306 |

Figure 16. Latin Square Arrangement for Test Sequence

| SPEED / PRESS | 1500 | 2000 | 2500 |
|---|---|---|---|
| 1500 | 307-1 | 300-5<br>306-1<br>308-2 | 305-3 |
| 2000 | 305-2 | 300-3<br>306-2<br>308-3 | 307-3 |
| 2500 | 307-2 | 304-4<br>306-3<br>308-1 | 305-1 |

Figure 17. Factorial Arrangement for Speed and Pressure

the test results at the 5% significance level. In addition, a similar analysis of the factorially arranged tests indicated that at the 5% significance level pump speed did not have a significant effect upon contaminant wear of a gear pump. The former result (sequence makes no difference) is a necessary condition for the research to have far reaching benefits. This means that a pump can be tested at several different pressures and the results will be meaningful. The second result is not surprising since the reported work of Rabinowicz and others, discussed in Chapter II, revealed a similar conclusion. The calculations of the statistical analysis performed are shown in Appendix F. The test results can be reduced, therefore, and the speed and sequence parameter can be eliminated by averaging. Once the data was reduced the effect of pressure was tested statistically and found to be significant for the larger particle sizes at the 5% significance level.

It should be noted that since the wear test was conducted by sequentially exposing the pump to increasing particle size ranges, the output flow was a function of the total clearance change. Thus, the change in flow or $\Delta Q$ was taken to be the difference between the output of the pump after the exposure and the flow of the pump initially. To be comparable then the Ferrographic density data had to be accumulated. That is, the change in flow after say the 0-20 micrometre size range exposure was the result of the clearance increase due to the 0-5, 0-10, and 0-20 micrometre exposures. Therefore, the total amount of wear debris generated must be proportional to the total clearance change. This can be illustrated as follows:

$$Q_{0-20} - Q_0 = \Delta Q_{0-20} \alpha \Delta h_{0-5} + \Delta h_{0-10} + \Delta h_{0-20} \qquad (21)$$

where:

$\Delta Q_{0-20}$ = flow degradation after the 0-20 micrometre size range exposure

$\Delta h_{0-5}$ = change in clearance due to 0-5 exposure

$\Delta h_{0-10}$ = change in clearance due to 0-10 exposure

$\Delta h_{0-20}$ = change in clearance due to 0-20 exposure

let:

$$\Delta h_{0-5} = h_{0-5} - h_0 \tag{22}$$

where:

$h_{0-5}$ = total clearance after 0-5 exposure

$h_0$ = initial clearance

and:

$$\Delta h_{0-10} = h_{0-10} - h_{0-5} \tag{23}$$

and

$$\Delta h_{0-20} = h_{0-20} - h_{0-10} \tag{24}$$

Substituting Equations (22), (23), and (24) into Equation (21) produces

$$\Delta Q_{0-20} \alpha\ h_{0-20} - h_0 \tag{25}$$

Now let:

$$\Delta h_{0-5} \alpha\ D54_{0-5} \tag{26}$$

and:

$$\Delta h_{0-10} \alpha\ D54_{0-10} \tag{27}$$

and:

$$\Delta h_{0-20} \alpha\ D54_{0-20} \tag{28}$$

Then it follows that:

$$\Delta Q_{0-20} \alpha \sum_{0}^{D} D54_{0-D} \tag{29}$$

Furthermore, it must be pointed out that in order to obtain the best possible Ferrographic density data various fluid volumes were used depending upon the debris concentration in the fluid. Therefore, the Ferrographic densities must be normalized to a constant volume to be comparable. In this case, all Ferrographic densities have been normalized to one millilitre of sample fluid.

Since the statistical analysis revealed that neither speed nor test sequence had a significant influence upon the test results, the results of tests which were conducted to evaluate these factors were merged with the other test results to produce a reduced data set. Table I shows the flow degradation results given in terms of the flow degradation ratio which is defined as the output flow. Table II reveals the total change in flow calculated by subtracting the output flow after each exposure from the initial flow. The reduced Ferrographic density data is given in Table III where the D54 readings, normalized to one millilitre have been accumulated.

The flow degradation results can be graphically illustrated by plotting the flow degradation ratio as a function of the upper limit of the particle size range for the various concentrations used in the test. Figure 18 shows the flow degradation ratio versus particle size range for the pump tests conducted at 2000 psid pressure differential. It can be seen from this figure that the curves for the various concentrations seem to be converging. This is not entirely surprising since at some particle size the wear process would be dominantly erosive where concentration would have a much reduced effect. The flow degradation ratio versus particle size range for the various pressure level utilized and a concentration of 20 mg/$\ell$ is shown in Figure 19. Here again the curves

TABLE I

AVERAGED FLOW DEGRADATION RATIO RESULTS

| PRESS (PSID) | CONT LEVEL (MG/ℓ) | FLOW DEGRADATION RATIO AT INDICATED SIZE $\frac{Q_f}{Q_i}$ | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | 0-5 | 0-10 | 0-20 | 0-30 | 0-40 | 0-50 | 0-60 | 0-70 | 0-80 |
| 1500 | 20 | 1.0 | 1.0 | 1.0 | 0.999 | 0.996 | 0.991 | 0.986 | 0.982 | 0.971 |
| | 150 | 1.0 | 1.0 | 0.987 | 0.987 | 0.867 | 0.804 | 0.720 | 0.661 | 0.644 |
| 2000 | 10 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 0.996 | 0.994 | 0.987 |
| | 20 | 1.0 | 1.0 | 1.0 | 0.996 | 0.991 | 0.982 | 0.975 | 0.965 | 0.954 |
| | 25 | 1.0 | 1.0 | 1.0 | 0.997 | 0.987 | 0.978 | 0.966 | 0.956 | 0.941 |
| | 75 | 1.0 | 1.0 | 0.997 | 0.981 | 0.952 | 0.920 | 0.884 | 0.849 | 0.798 |
| | 150 | 1.0 | 1.0 | 0.990 | 0.944 | 0.885 | 0.842 | 0.765 | 0.712 | 0.653 |
| | 300 | 1.0 | 0.997 | 0.959 | 0.875 | 0.769 | 0.707 | 0.582 | | |
| 2500 | 20 | 1.0 | 1.0 | 1.0 | 0.998 | 0.990 | 0.979 | 0.969 | 0.951 | 0.935 |
| | 150 | 1.0 | 1.0 | 0.992 | 0.947 | 0.876 | 0.796 | 0.717 | 0.655 | 0.636 |

TABLE II

AVERAGED FLOW DEGRADATION RESULTS

| PRESS (PSID) | CONT LEVEL (MG/ℓ) | FLOW DEGRADATION AT INDICATED SIZE, ΔQ | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | 0-5 | 0-10 | 0-20 | 0-30 | 0-40 | 0-50 | 0-60 | 0-70 | 0-80 |
| 1500 | 20 | 0 | 0 | 0 | .01 | .05 | .10 | .16 | .22 | .34 |
| | 150 | 0 | 0 | .15 | .72 | 1.52 | 2.24 | 3.19 | 3.87 | 4.06 |
| 2000 | 10 | 0 | 0 | 0 | 0 | 0 | 0 | .04 | .07 | .15 |
| | 20 | 0 | 0 | 0 | .05 | .10 | .19 | .27 | .39 | .51 |
| | 25 | 0 | 0 | 0 | .04 | .16 | .27 | .42 | .54 | .73 |
| | 75 | 0 | 0 | .04 | .23 | .57 | .95 | 1.37 | 1.79 | 2.39 |
| | 150 | 0 | 0 | .12 | .69 | 1.41 | 1.94 | 2.89 | 3.54 | 4.26 |
| | 300 | 0 | .04 | .51 | 1.56 | 2.87 | 3.65 | 5.20 | | |
| 2500 | 20 | 0 | 0 | 0 | .02 | .11 | .24 | .35 | .55 | .73 |
| | 150 | 0 | 0 | .09 | .62 | 1.46 | 2.41 | 3.34 | 4.07 | 4.30 |

TABLE III

AVERAGED FERROGRAPHIC DENSITY RESULTS

| PRESS (PSID) | CONT LEVEL (MG/ℓ) | FERROGRAPHIC DENSITY AFTER INDECATED SIZE, Δ D54/mℓ | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | 0-5 | 0-10 | 0-20 | 0-30 | 0-40 | 0-50 | 0-60 | 0-70 | 0-80 |
| 1500 | 20 | 1.13 | 2.4 | 4.37 | 6.57 | 9.10 | 12.04 | 15.69 | 19.61 | 22.8 |
| | 150 | 7.95 | 16.85 | 44.85 | 88.52 | 120.85 | 155.18 | 206.85 | 254.52 | 294.85 |
| 2000 | 10 | 1.11 | 2.52 | 4.33 | 6.04 | 7.53 | 9.24 | 11.44 | 13.27 | 15.22 |
| | 20 | 1.05 | 2.78 | 4.85 | 7.56 | 10.98 | 14.72 | 18.18 | 22.52 | 26.51 |
| | 25 | 1.75 | 4.28 | 8.21 | 11.46 | 16.18 | 19.58 | 24.35 | 28.20 | 34.40 |
| | 75 | 3.85 | 7.52 | 12.95 | 21.32 | 33.32 | 44.92 | 56.52 | 68.52 | 78.52 |
| | 150 | 8.40 | 19.0 | 47.67 | 77.17 | 118.34 | 141.17 | 174.47 | 201.3 | 236.63 |
| | 300 | 19.20 | 42.75 | 87.00 | 152.40 | 218.40 | 304.65 | 378.82 | | |
| 2500 | 20 | 1.42 | 3.44 | 6.26 | 10.04 | 14.73 | 19.23 | 24.76 | 31.13 | 35.88 |
| | 150 | 5.0 | 19.8 | 51.8 | 86.8 | 151.47 | 202.8 | 272.47 | 333.14 | 415.14 |

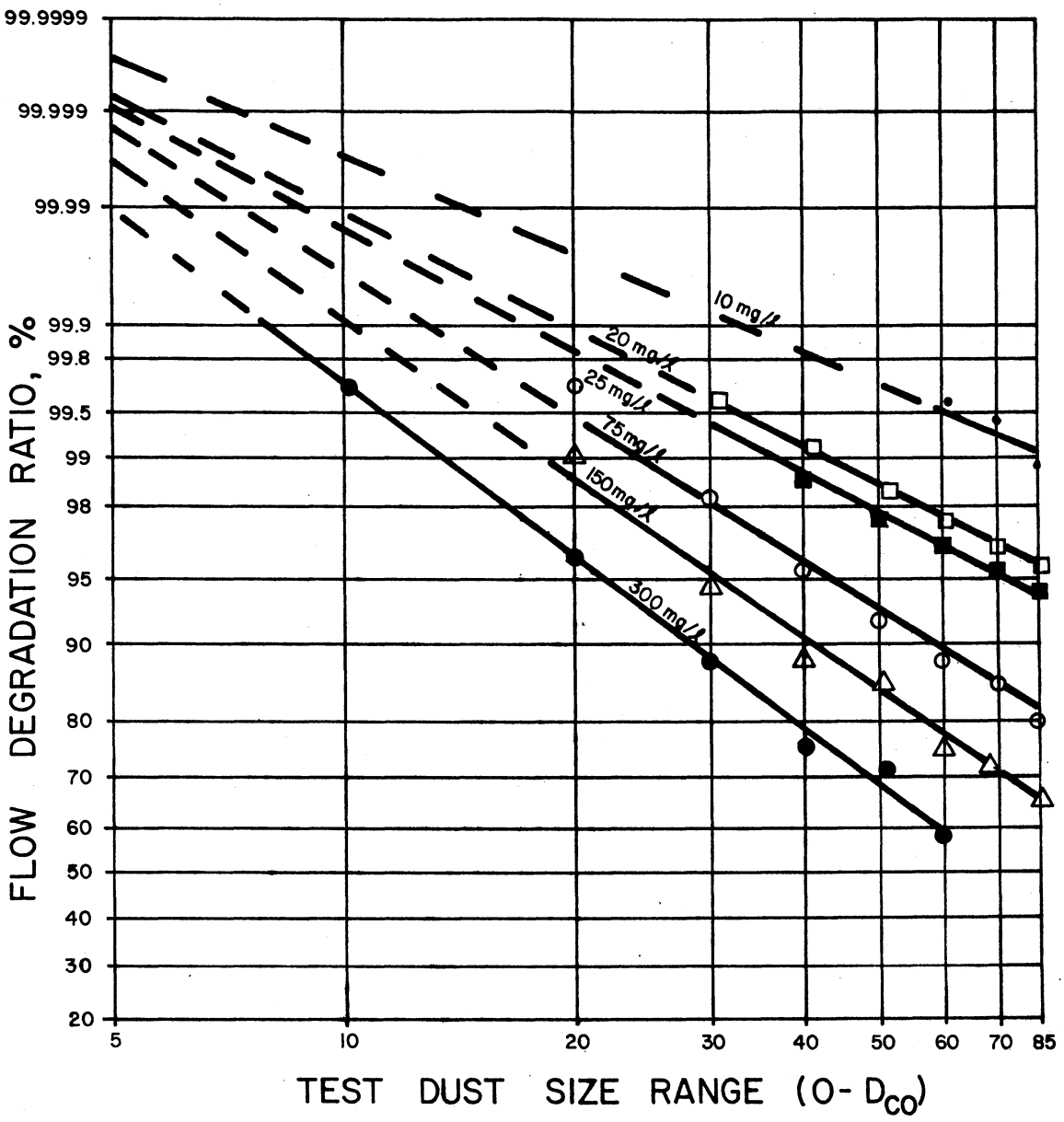


Figure 18. Flow Degradation Ratio as a Function of Particle Size Range for Various Concentrations at 2000 psid

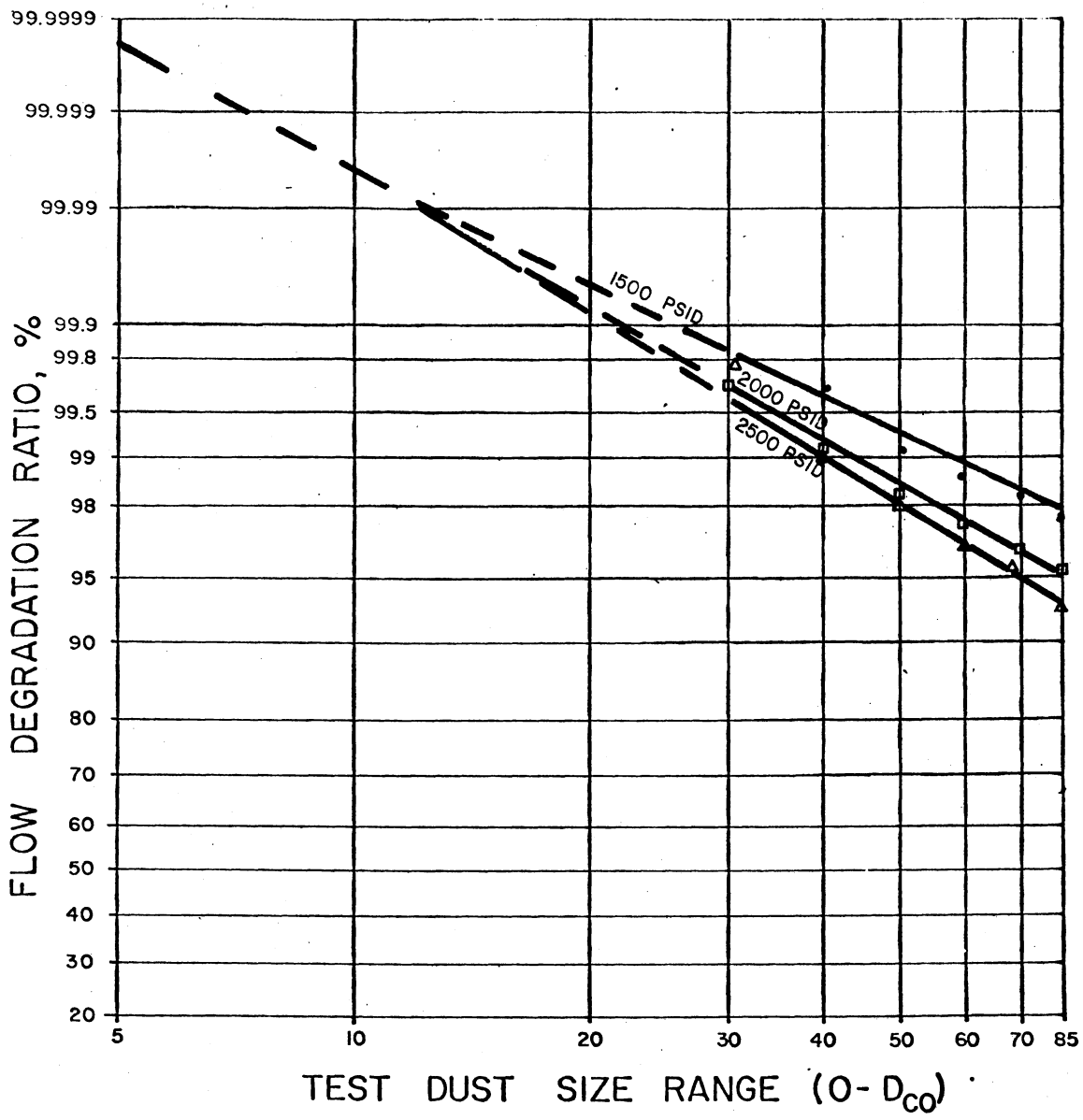


Figure 19. Flow Degradation Ratio as a Function of Particle Size Range for Various Pressures at 20 mg/l

seem to converge implying that below a given particle size range pressure does not have a significant influence upon the contaminant wear process for a gear pump.

The Ferrographic density data from Table III can best be graphically illustrated by plotting the $\Sigma D54/ml$ as a function of the particle size range exposed to the gear pump. Such curves have been plotted for various concentrations in Figure 20 and for various pressures in Figure 21. The curves shown in these two figures are least squares best fit of a power function to the data shown. It can be seen from these curves that concentration at a given pressure tends to move the curve upward in a parallel fashion. On the other hand, pressure at a given concentration causes the slope of the curves to be altered. Considering the data shown in Figures 18 and 20, it can be seen why 20 mg/$\ell$ was selected for the bulk of the tests. At this concentration, it was felt that there was reasonable flow degradation and wear debris generation to produce a meaningful correlation. At 25 mg/$\ell$, the flow degradation was considered excessive and at 10 mg/$\ell$ the wear debris generation as measured Ferrographically was low.

## Verification of Ferrographic Wear Model

The Ferrographic Wear Model (Equation (20)) as presented in Chapter IV stated that the Ferrographic density was a power function of the particle size range exposed to the gear pump. This part of the model was verified by actually fitting a power function to the test data as given in Table III. The equations developed for the various pressures and contaminant levels of the tests are shown in Table IV along with the coefficient of determination. As can be seen from Table IV the

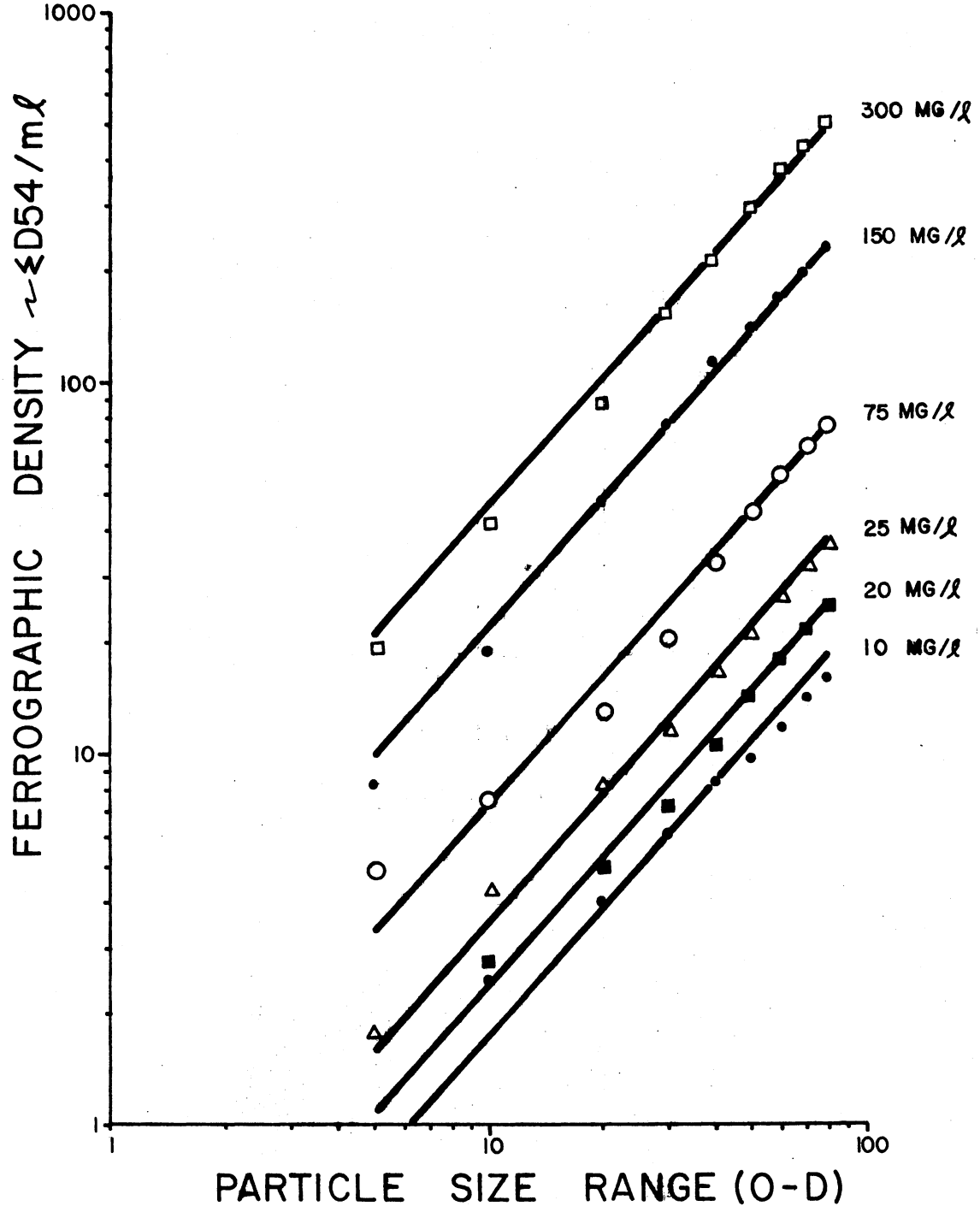


Figure 20. Ferrographic Density as a Function of Particle Size Range for Various Concentrations at 2000 psid

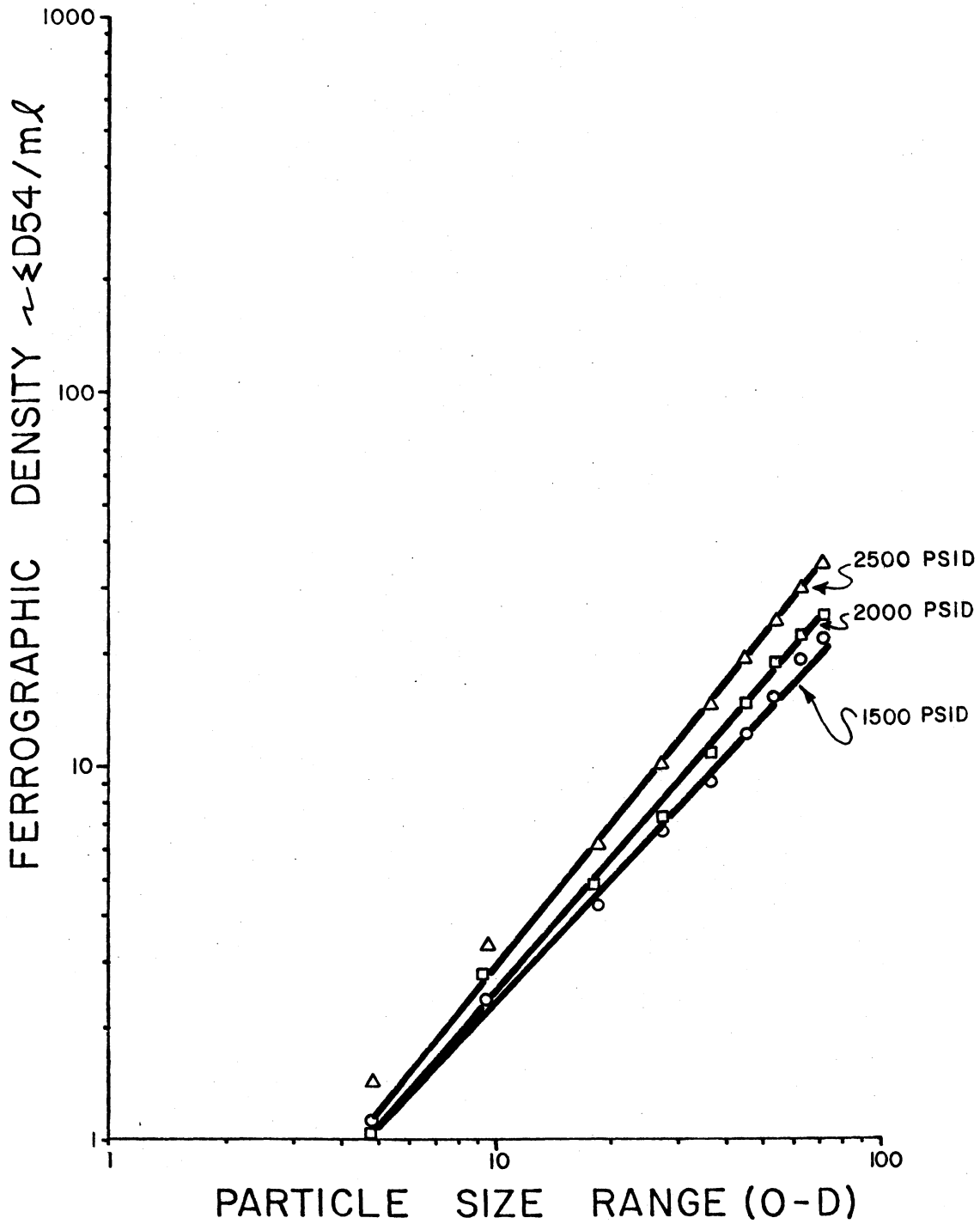


Figure 21. Ferrographic Density as a Function of Particle Size Range for Various Pressures at 20 mg/l

TABLE IV

SUMMARY OF EQUATION FOR FERROGRAPHIC DENSITIES

| PRESSURE (PSID) | CONT. LEVEL MG/ℓ | EQUATION | COEF. OF DETER |
|---|---|---|---|
| 1500 | 20 | $y = 0.19\ D^{1.07}$ | $r^2 = 0.991$ |
| | 150 | $y = 2.20\ D^{1.07}$ | $r^2 = 0.995$ |
| 2000 | 10 | $y = 0.13\ D^{1.13}$ | $r^2 = 0.997$ |
| | 20 | $y = 0.17\ D^{1.13}$ | $r^2 = 0.996$ |
| | 25 | $y = 0.25\ D^{1.13}$ | $r^2 = 0.998$ |
| | 75 | $y = 0.52\ D^{1.13}$ | $r^2 = 0.995$ |
| | 150 | $y = 1.57\ D^{1.13}$ | $r^2 = 0.997$ |
| | 300 | $y = 3.29\ D^{1.13}$ | $r^2 = 0.998$ |
| 2500 | 20 | $y = 0.22\ D^{1.15}$ | $r^2 = 0.996$ |
| | 150 | $y = 2.12\ D^{1.15}$ | $r^2 = 0.991$ |

$$y = \Sigma \frac{D54}{M\ell}$$

experimental data agreed closely with the theoretical equation form. These defined equations can be substituted into the equation of the Ferrographic Wear Model which describes the total flow change, $\Delta Q$, as a function of the clearance change, $\Delta h$. In order to accomplish this it is necessary to use the expression which states that the accumulated Ferrographic density value is proportional to the equivalent clearance change, $\Delta h$, due to contaminant wear.

The equations given in Table IV were substituted into the Ferrographic Wear Model and the data shown in Table II was used to completely define the model. These results are shown graphically in Figures 22, 23, and 24 for tests conducted at 1500, 2000, and 2500 psid respectively. In these figures the solid lines were obtained from the model while the various symbols identified on each figure show the actual data values. The dashed part of each line shows the portion of the curve undefined by either the model or the data. Except for the data obtained at 10 mg/$\ell$ and 2000 psid (Figure 23) the model is a very good representation of the test data. The only explanation of the obvious trend reversal shown by the 10 milligram per litre curve in Figure 23 lies in the magnitude of both the Ferrographic data and the flow degradation results. There is considerable error introduced at such low levels and this was the primary reason for the use of 20 milligrams per litre in most of the tests.

It is felt that the comparison shown in Figures 22, 23, and 24 adequately demonstrates that model can be verified for a given gear pump. This verification implies that the primary influence of contaminant wear is to increase the composite clearance of a gear pump. This change in clearance is reflected in two ways -- generation of wear debris and degradation in output flow. The model indicates that both of these

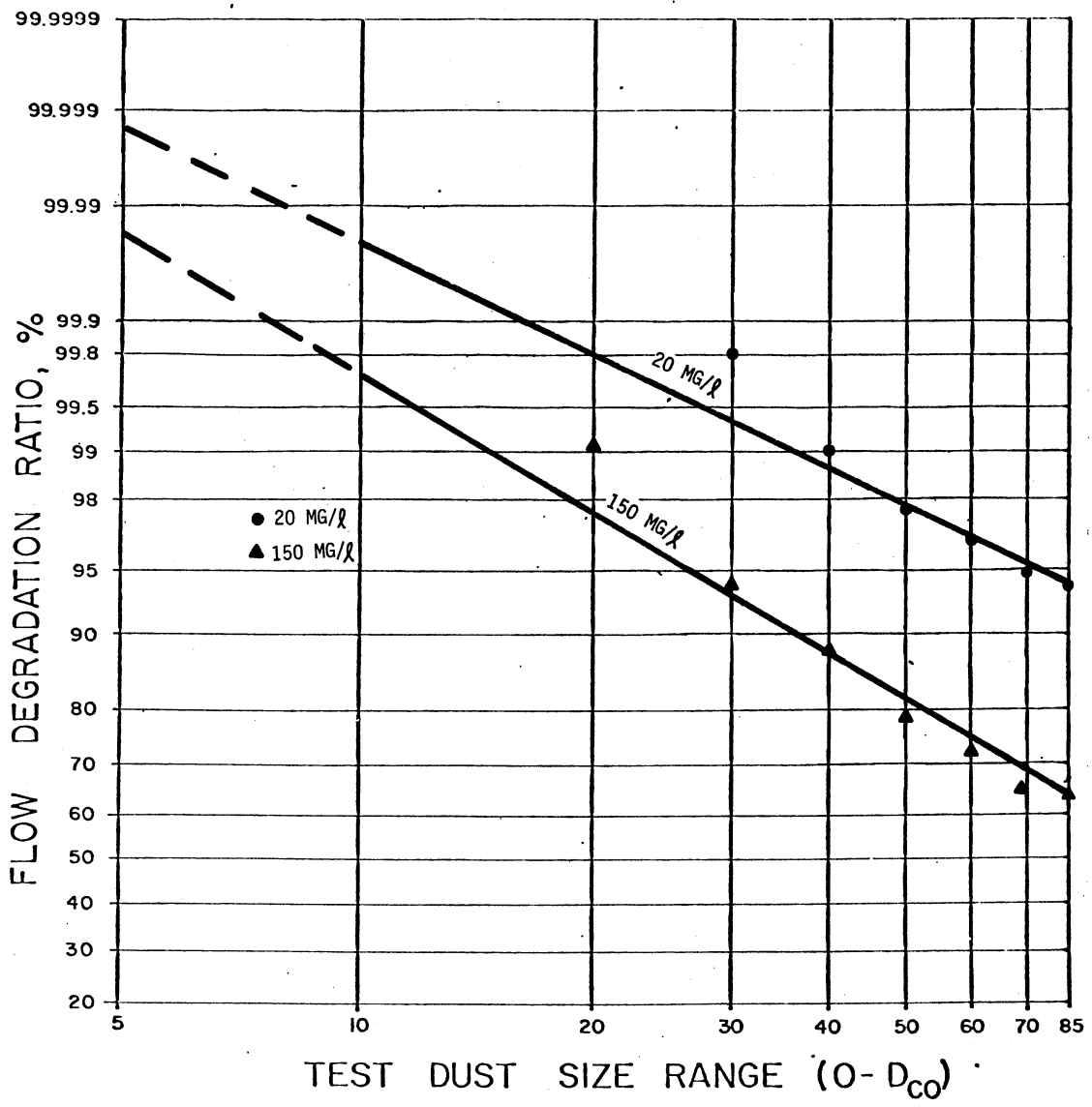


Figure 22. Comparison of Calculated and Measured Flow Degradation Ratio at 1500 psid

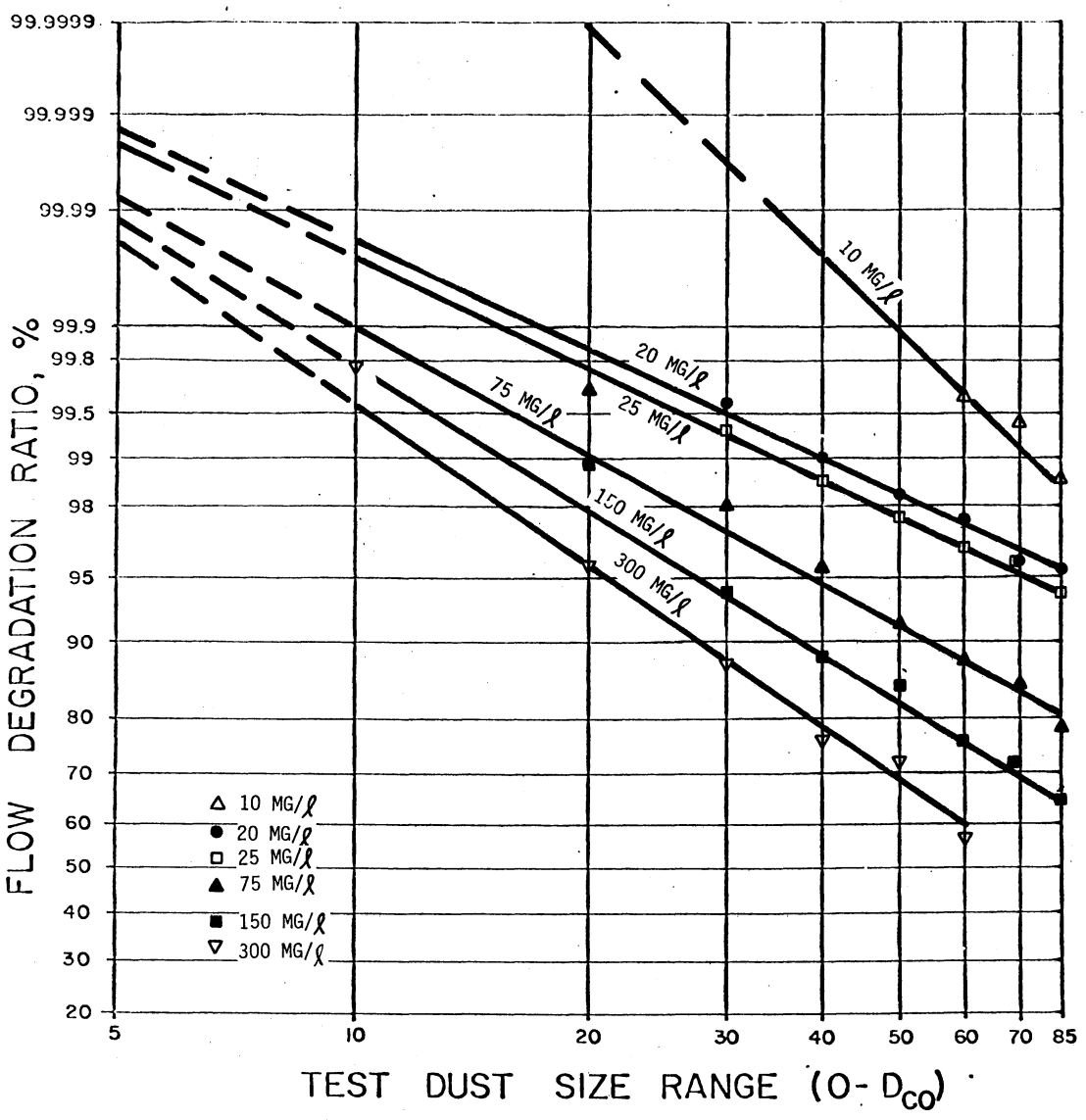


Figure 23. Comparison of Calculated and Measured Flow Degradation Ratio at 2000 psid

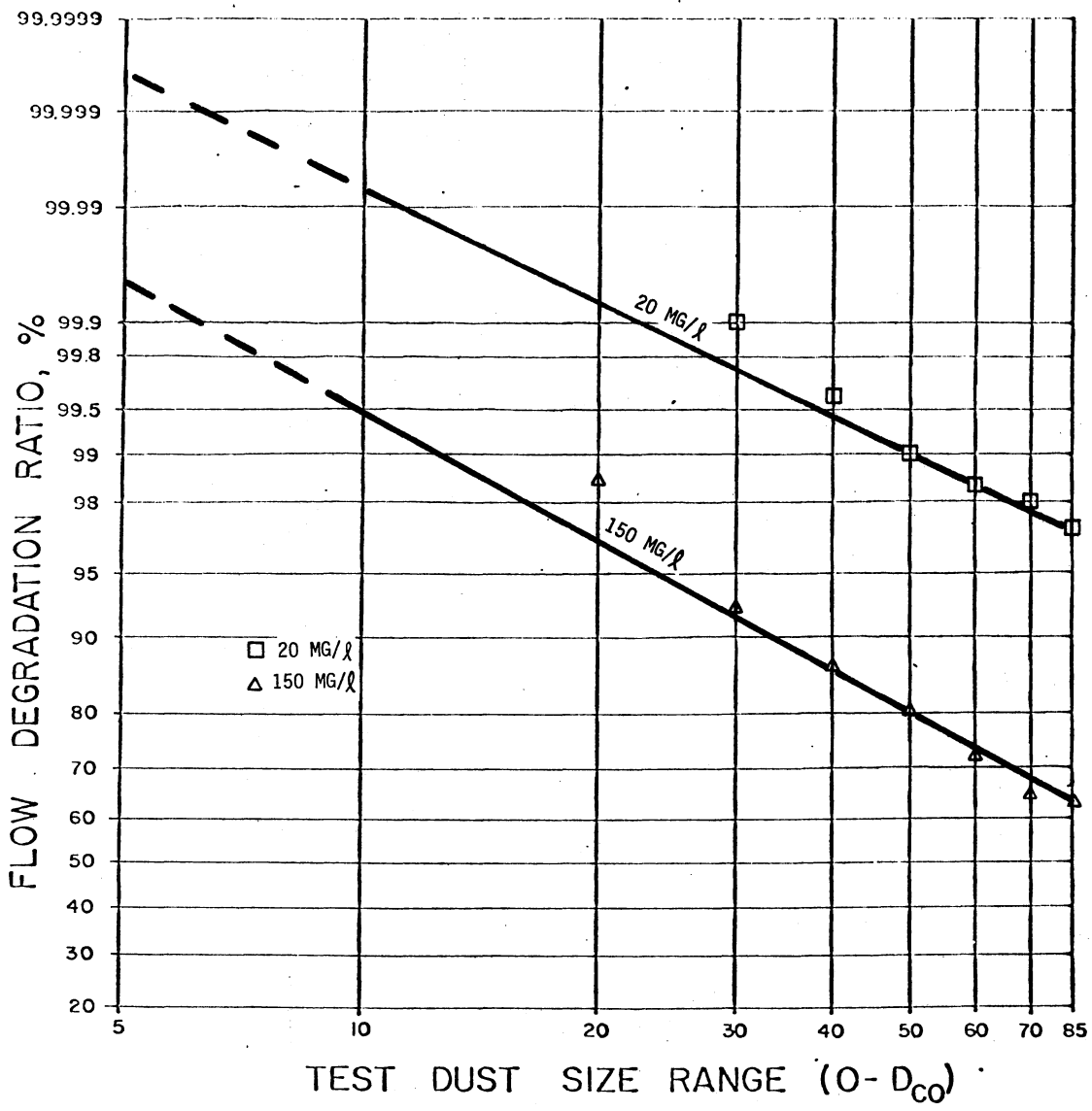


Figure 24. Comparison of Calculated and Measured Flow Degradation Ratio at 2500 psid

variables are proportional to the change in composite clearance. Although these conclusions can be deduced from an engineering appraisal of a gear pump, there was no way to document the phenomenon until the introduction of the Ferrographic oil analysis technique. The significance of the discoveries made during this research effort are discussed in the next chapter.

# CHAPTER VI

## SIGNIFICANCE OF RESEARCH

Contaminant wear in hydraulic components has long been recognized as a major factor in the life and reliability of such components. Attempts to reduce the deliterious influence of particulate contamination entrained in the circulating fluid of a hydraulic system have taken two courses. Probably, the most apparent solution to contaminant wear is the removal of these contaminant particles. Work in filtration of particulate contamination has produced much improvement in component life. The second approach to the problem of contaminant wear is concerned with the design of the components themselves. Through judicial design (configuration as well as materials) most hydraulic components can be made less sensitive to contaminant attack.

Improvements in the contaminant wear characteristics of hydraulic components have been hampered by two major obstacles. One stumbling block is associated with the inability to study the wear process directly while the second was the lack of a method to measure the results of the process in terms of the component function. Since, during operation of the component, the wear area is totally enclosed (to contain the fluid) any direct observations are impossible and disassembly is impractical. Therefore, measurement of the results of the wear process were forced to take an indirect form. The most widely accepted technique to evaluate contaminant wear is to measure the

performance degradation due to the process. In order to accomplish this an accelerated basis the contamination level exposed to the component had to be high enough to produce sufficient performance degradation to be readily and accurately measured. This requirement resulted in the use of 300 milligrams per litre in most contaminant sensitivity tests.

In hydraulic gear pumps such a high contamination level produced other problems. The most serious of these problems was the fact that, in most cases, the pump was totally destroyed during a test using only one set of operating conditions. If data was desired at any other condition (e.g., a higher or lower pressure) a new pump had to be used. This is both expensive and time consuming. With the introduction of the Ferrographic wear analysis technique, however, a new tool became available which offered a means of measuring the results of the contaminant wear process at much lower contamination levels. At these lower levels contaminant induced damage would be reduced and perhaps many tests could be conducted on the same pump.

Based upon the results of this research a modified contaminant sensitivity test can be developed for hydraulic pumps. The modification would include the reduction of the contamination level from 300 milligrams per litre to 20 milligrams per litre. Fluid samples would be extracted during each exposure for Ferrographic analysis. The proposed modified test would subject the various particle size ranges to the pump on a sequential basis. That is, a particle size range of 0-5 micrometres would be used first, followed by 0-10, 0-20, etc. micrometres. However, the test would continue in this manner only until three flow degradation points have been recorded.

Based upon experience, it would be expected that the modified test

would be conducted until a particle size range of 0-40 or 0-50 had been exposed to the pump. At this point in the test, the pump would have exhibited a measurable flow degradation at three contaminant exposures. Furthermore, Ferrographic density data would be available at 5 or 6 exposures. This would provide sufficient data to define the Ferrographic Wear Model which then could be used to predict the degradation at all nine contaminant particle size ranges. It should be noted that the total flow degradation exhibited by the pumps tested as part of the effort after exposure to 0-50 micrometre size range was approximately 2%. The operating pressure of the pump could then be increased or decreased to obtain similar data at a different pressure. This whole process could be repeated, at least on the pumps tested here, at four different pressures and the total flow degradation would not exceed 8-10%.

The fact that the test data presented here failed to show a significant influence from pump speed is important. This implies that speed is not a parameter of concern in the contaminant wear characteristics of a hydraulic gear pump. The true advantage of this discovery lies in the fact that very large pumps can be tested at lower than rated speed without unduly influencing the contaminant wear evaluation. In addition, the number of tests required on a given pump can be reduced to only pressure consideration. Therefore, a pump which produces 100 gallons per minute at 2500 revolutions per minute could be evaluated on a test facilities with a maximum flow capability of 60 gallons per minute by merely conducting the test at a speed lower than 2500 RPM.

Another important factor resulting from the work accomplished by

this effort is that the test sequence does not significantly influence the outcome. Therefore, if it is desired to evaluate a pump at four operating pressures, the evaluation at one pressure does not bias the results at another pressure. This assumes, of course, that the total flow degradation of the pump is not excessive. In addition, if a pump is assessed at, say four pressures, and some time later a new pump is evaluated at a different set of pressure levels the results of both tests should correlate provided the design of the pump has not been altered.

It is felt that through the work presented here, the Ferrographic wear analysis technique has been shown to be an effective method for evaluating contaminant wear. The isolation mechanisms used in this process are ideally suited to contaminant wear tests. In such experiments, test contaminants are intentionally injected into the circulating fluid to produce a control contaminant wear process. The analysis or measurement of the wear debris generated during the test would be impossible unless the debris can be separated from the introduced contamination. The correlation obtained between Ferrographic density and flow degradation data through consideration of the clearance change indicates that the Ferrographic technique is an effective means of isolating the wear debris from the extraneous material. Once separated a great deal of information can be obtained from the wear debris. Although not included here, the size and shape of the wear debris can be used to deduce facts concerning the nature of the contaminant attack. Furthermore, elemental analysis of the debris collected on a Ferrogram can be performed to learn the major constituent present. However, such appraisals are more rewarding when the wear process is not controlled.

There are several areas of investigation which would add significantly to the body of knowledge associated with contaminant wear that were not a part of this study. The scope of this effort was limited to a manageable extent by including only pressure and speed as operating variables while evaluating both concentration and particle size range of the test contaminant. In addition, this is the first attempt to utilize the Ferrographic data to evaluate the contaminant wear of any hydraulic component. The following section of this chapter presents some of the major areas where it is felt that additional studies can make major contributions.

## Recommendations for Further Studies

While the gear pump is widely used in hydraulic applications there are other types of pumps worthy of consideration. For example, the vane pump is an old standby in the hydraulic industry. Furthermore, with the advent of high pressure and closed center systems, the popularity of the piston pump is rising. It is possible since the leakage paths may be different in the various types of hydraulic pumps that the Ferrographic Wear model would need to be modified for vane and piston pumps.

The following is an outline of the various investigations which have come to light as a result of the research effort:

1. The study of both vane and piston pumps is a natural extension of this effort.
2. One additional operating parameter which was not evaluated in this work is the fluid temperature. Obviously, the viscosity of the hydraulic fluid is a function of

temperature and also is a parameter in the hydrodynamic lubrication theory. An evaluation should be made concerning the influence of temperature on contaminant wear of pumps along with any interaction between fluid temperature and the output temperature.

3. It was quite interesting to note that the Ferrographic density was a power function of the upper limit of the particle size range exposed to the pump. While other researchers using entirely different testing concepts have observed this relationship none have presented a concept which explains this trend. It is possible that a noteworthy contribution could be made if such a concept was developed.

4. The coefficient of the power function describing the $\Sigma$ D54/ml relationship to particle size range is dependent upon the concentration of the contaminant exposure while the exponent is a function of the output pressure. The exact nature of these dependency have not been characterized in this effort. An investigation concerning these parameters and their meaning to the engineering world would be valuable.

5. The contaminant wear characteristics of other hydraulic components such as valves has been very difficult to evaluate by performance degradation alone. The application of Ferrographic analysis in the evaluation of contaminant wear in other hydraulic components should be initiated.

6. The effort should be continued to develop a modified contaminant sensitivity based upon Ferrographic analysis.

The basis for such modification have been proposed from this effort. However, a complete procedure should be formulated and verified as to decrimmination and repeatability. Such an effort would provide a powerful tool for assessing the contaminant wear characteristics of not only hydraulic pumps but other components as well.

This investigation has produced a great deal of valuable data and has developed useful concepts. However, a continuing thrust should be made to understand the ramification of the information obtained and to apply the Ferrographic method of wear analysis to other applications. To the author's knowledge this is the only study made in the use of Ferrographic techniques for study of wear in hydraulic components and systems. In addition, the Ferrograph is uniquely suited to contaminant wear investigations where a test contaminant is introduced into a system. This fact should be capitalized upon in both hydraulic systems and lubrication systems.

# CHAPTER VII

# SUMMARY AND CONCLUSIONS

## Summary

The fundamental hypothesis investigated in this effort was founded upon the fact that the primary influence of contaminant wear in a gear pump is the enlargement of the composite clearances within the pump. This increase in clearance is reflected by both the generation of wear debris and the loss of output flow at a given pressure. At the initiation of this effort, it was proposed that the amount of wear debris generated was directly proportional to the change in pump clearance. Thus by measuring the wear debris concentration in the circulating fluid after exposing the pump to a given and controlled contaminant environment the resulting increase in clearance could be assessed.

The Ferrographic wear analysis method was used to appraise the wear debris concentration. However, since it was impossible to measure either the initial clearances or the change of clearance within a pump, a second parameter (flow degradation) was used to evaluate the hypothesis. This required the development of a Ferrographic Wear Model which included both the Ferrographic parameters as well as flow degradation. Thus, the Ferrographic density data was used to develop a flow degradation model which in turn was fit to the flow degradation data. The goodness of fit between the model and the

data was used as a criterion for acceptability of the model.

There were 24 pump contaminant wear tests conducted in this effort along with five pump performance tests and numerous experiments associated with the Ferrographic technique. The results of the performance tests were used to determine the form of the flow degradation model. The Ferrographic experiments were conducted to evaluate the capabilities of the technique in terms of linearity, saturation and repeatability. Initial tests with the Ferrograph reveal a need for improvement which was accomplished. During the pump contaminant wear tests samples were extracted at each contaminant exposure and the output flow was carefully measured. The pumps were evaluated using the following parameters as test variables.

1. Outlet pressure - 1500, 2000, 2500 psi
2. Shaft speed - 1500, 2000, 2500 RPM
3. Contaminant concentration (10, 20, 25, 75, 150, 300 milligrams per litre)
4. Particle size range (0-5, 0-10, 0-20, 0-30, 0-40, 0-50, 0-60, 0-70, 0-80 micrometres)

The test plan was formulated in such a manner that the influence of pump speed, outlet pressure, and testing sequence could all be assessed through standard statistical techniques. It was proposed that by using wear debris analysis the contamination level of the standard wear test could be dratically reduced. At this reduced contaminant concentration destruction due to contaminant wear would also be reduced and more than one test could be conducted on the same pump specimen. Thus, the test sequence aspect refers to the influence of conducting more than one contaminant wear test on the same pump.

The results of the statistical analysis revealed that speed and sequence had insignificant effect on the test results but that pressure could not be ignored. Thus, the results of tests conducted in various sequences and at different speeds were averaged with the other test data to provide a stronger data base.

The Ferrographic density data ($\Sigma$D54/ml) was used to formulate expressions which described the wear debris generation as a function of the significant variables of the testing program. This phase of effort revealed that the amount of debris generated versus particle size range was an excellent fit to an exponential model (log-log). The coefficient of this particular power function was found to be related to the concentration in milligrams per litre of the contaminant environment while the exponent indicated a dependency upon the outlet pressure of the test pump. The Ferrographic density values were assumed to be proportional to the clearance change within the pump and the flow degradation data was utilized in determining the constant or proportionally. Therefore, a complete Ferrographic Wear Model was developed and compared to the test data. This comparison revealed excellent correlation between the flow degradation ratios calculated from the model and the ratios derived directly from the actual output flow data.

## Conclusions

The accomplishments of this research effort have contributed significantly to the area of contaminant wear. Prior to this work the use of wear debris to evaluate the contaminant wear of a hydraulic component had not been successfully achieved. Through the use of the Ferrographic oil analysis technique, this effort has shown that the amount of debris

generated by a contaminant wear process can be used to evaluate the degree of wear in a gear pump. In addition, since flow loss is the normal manner used by the engineering world for expressing wear in a hydraulic gear pump, this research work has shown that the amount of wear debris generated will correlate with the accompanying flow degradation through proper consideration of the clearance changes.

The noteworthy contributions resulting from this research effort can be outlined as follows:

1. As a result of the extensive modifications to the Ferrograph operating technique and the associated equipment made as a necessary part of this study, a repeatable and viable wear debris analysis method was evolved.
2. A major discovery resulting from this investigation is that the amount of wear debris generated from a gear pump due to contaminant exposure is a power function of the particle size range exposed and that:
    a. The coefficient of this power function is dependent upon the concentration of the contaminant environment which produced the debris, and that
    b. The exponent of this power function is related to outlet pressure imposed.
3. Based upon the results of actual pump tests conducted in accordance with a factorially arranged test plan, pump speed was shown to have no significant influence upon the contaminant wear of a gear pump.
4. The Ferrographic Wear Model developed and advanced in this study has been shown to accurately characterize the relationships for

wear debris generation and flow degradation associated with a gear pump.

5. It was demonstrated by this study that by using a fluid environment having a contaminant concentration of only 20 milligrams/litre, a single pump can be sequentially (at least three times) tested at different operating conditions without significantly biasing the test results. This means that the contaminant tolerance of a gear pump can be completely defined over a broad spectrum of operating conditions using a single pump.
6. A practical and significant engineering contribution to international fluid power standardization was made by this research effort in providing a firm basis for a new contaminant sensitivity test in which a drastically reduced contamination level (20 MG/$\ell$ as compared to 300 MG/$\ell$ in the standard test) is used with a single pump to assess its tolerance at different operating conditions (pressure, temperature, etc.).

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# APPENDIX A

## PUMP PERFORMANCE DATA

The output flow at various outlet pressures and shaft speeds were measured for five pumps. The pumps utilized for this phase of effort carried the following identification numbers 300, 301, 302, 303, 311. Pump No. 300 was evaluated at 2000 psi outlet pressure while pump No. 301 was tested at 1500, 2000, and 2500 psi. Pumps 302 and 303 were appraised at 500, 1000, 1500, 2000, and 2500 psi. In all of these tests, output flow was measured at both increasing and decreasing speeds with an average result used. Pump No. 311 was tested at constant speeds of 1500, 2000, and 2500 RPM while the pressure was varied from 600 to 2500 psi. The following tables show the actual flow results obtained.

TABLE V

OUTPUT FLOW DATA FOR PUMP NO. 300

| SPEED (RPM) | OUTPUT FLOW AT PRESSURE |
|---|---|
| | 2000 psi |
| 1000 | 5.50 |
| 1100 | 6.19 |
| 1200 | 6.84 |
| 1300 | 7.50 |
| 1400 | 8.15 |
| 1500 | 8.81 |
| 1600 | 9.47 |
| 1700 | 10.14 |
| 1800 | 10.79 |
| 1900 | 11.47 |
| 2000 | 12.09 |
| 2100 | 12.77 |
| 2200 | 13.44 |
| 2300 | 14.09 |
| 2400 | 14.74 |
| 2500 | 15.39 |

TABLE VII

OUTPUT FLOW DATA FOR PUMP NO. 301

| SPEED (RPM) | OUTPUT FLOW AT INDICATED PRESSURE (GPM) | | |
|---|---|---|---|
| | 1500 psi | 2000 psi | 2500 psi |
| 1000 | 5.76 | 5.63 | 5.39 |
| 1100 | 6.41 | 6.29 | 6.06 |
| 1200 | 7.09 | 6.96 | 6.73 |
| 1300 | 7.71 | 7.62 | 7.39 |
| 1400 | 8.41 | 8.26 | 8.05 |
| 1500 | 9.05 | 8.94 | 8.73 |
| 1600 | 9.67 | 9.54 | 9.37 |
| 1700 | 10.34 | 10.18 | 10.07 |
| 1800 | 11.00 | 10.85 | 10.70 |
| 1900 | 11.65 | 11.50 | 11.37 |
| 2000 | 12.30 | 12.17 | 11.99 |
| 2100 | 12.96 | 12.82 | 12.71 |
| 2200 | 13.59 | 13.48 | 13.33 |
| 2300 | 14.22 | 14.15 | 13.98 |
| 2400 | 14.88 | 14.80 | 14.64 |
| 2500 | 15.52 | 15.42 | 15.26 |

TABLE VII

OUTPUT FLOW DATA FOR PUMP NO. 302

| SPEED (RPM) | OUTPUT FLOW AT INDICATED PRESSURE (GPM) | | | | |
|---|---|---|---|---|---|
| | 500 psi | 1000 psi | 1500 psi | 2000 psi | 2500 psi |
| 1000 | 6.19 | 5.97 | 5.86 | 5.63 | 5.48 |
| 1100 | | | 6.49 | 6.30 | 6.15 |
| 1200 | | | 7.13 | 6.94 | 6.75 |
| 1300 | | | 7.77 | 7.62 | 7.41 |
| 1400 | | | 8.43 | 8.24 | 8.05 |
| 1500 | 9.39 | 9.22 | 9.03 | 8.88 | 8.69 |
| 1600 | | | 9.71 | 9.56 | 9.33 |
| 1700 | | | 10.34 | 10.22 | 10.03 |
| 1800 | | | 10.98 | 10.87 | 10.68 |
| 1900 | | | 11.65 | 11.52 | 11.33 |
| 2000 | 12.57 | 12.42 | 12.29 | 12.19 | 12.00 |
| 2100 | | | 12.94 | 12.82 | 12.65 |
| 2200 | | | 13.61 | 13.44 | 13.34 |
| 2300 | | | 14.26 | 14.11 | 13.99 |
| 2400 | | | 14.94 | 14.72 | 14.65 |
| 2500 | 15.74 | 15.67 | 15.57 | 15.44 | 15.30 |

TABLE VIII

OUTPUT FLOW DATA FOR PUMP NO. 303

| SPEED (RPM) | OUTPUT FLOW AT INDICATED PRESSURE (GPM) | | | | |
|---|---|---|---|---|---|
| | 500 psi | 1000 psi | 1500 psi | 2000 psi | 2500 psi |
| 1000 | 6.03 | 5.73 | 5.46 | 5.13 | 4.59 |
| 1100 | | | 6.10 | 5.78 | 5.19 |
| 1200 | | | 6.75 | 6.40 | 5.97 |
| 1300 | | | 7.43 | 7.07 | 6.64 |
| 1400 | | | 8.01 | 7.75 | 7.30 |
| 1500 | 9.18 | 8.95 | 8.63 | 8.39 | 7.96 |
| 1600 | | | 9.30 | 9.11 | 8.67 |
| 1700 | | | 10.10 | 9.65 | 9.31 |
| 1800 | | | 10.66 | 10.30 | 9.96 |
| 1900 | | | 11.33 | 10.96 | 10.62 |
| 2000 | 12.36 | 12.15 | 11.94 | 11.56 | 11.31 |
| 2100 | | | 12.59 | 12.23 | 11.96 |
| 2200 | | | 13.23 | 12.92 | 12.65 |
| 2300 | | | 13.86 | 13.65 | 13.30 |
| 2400 | | | 14.49 | 14.30 | 13.92 |
| 2500 | 15.59 | 15.36 | 15.13 | 15.01 | 14.55 |

TABLE IX

OUTPUT FLOW DATA FOR PUMP NO. 311

| OUTLET PRESSURE (PSI) | OUTPUT FLOW AT INDICATED SPEED (GPM) | | | |
|---|---|---|---|---|
| | 1500 RPM | 2000 RPM | 2500 RPM | |
| 2500 | 9.31 | 12.58 | 16.15 | |
| 2400 | 9.35 | 12.59 | 16.18 | |
| 2300 | 9.37 | 12.61 | 16.17 | |
| 2200 | 9.41 | 12.61 | 16.17 | |
| 2100 | 9.43 | 12.61 | 16.18 | |
| 2000 | 9.45 | 12.65 | 16.18 | |
| 1900 | 9.48 | 12.67 | 16.22 | |
| 1800 | 9.52 | 12.69 | 16.24 | |
| 1700 | 9.54 | 12.73 | 16.28 | |
| 1600 | 9.54 | 12.73 | 16.30 | |
| 1500 | 9.58 | 12.77 | 16.32 | |
| 1400 | 9.60 | 12.77 | 16.34 | |
| 1300 | 9.62 | 12.80 | 16.36 | |
| 1200 | 9.64 | 12.84 | 16.36 | |
| 1100 | 9.66 | 12.84 | 16.39 | |
| 1000 | 9.69 | 12.88 | 16.41 | |
| 900 | 9.73 | 12.90 | 16.41 | |
| 800 | 9.73 | 12.94 | 16.43 | |
| 700 | 9.77 | 12.94 | 16.45 | |
| 600 | 9.81 | 12.97 | 16.51 | |

# APPENDIX B

# TEST FACILITIES

The test facilities utilized in the data acquisition phases of this research investigation included a pump contaminant wear test stand, a pump drive system and a Ferrographic Oil analysis system. The contaminant wear test stand and the pump drive unit are shown pictorially in Figures 25 and 26. In Figure 25 the wear test stand is shown in the right hand portion of the figure while the pump drive unit is in the background to the left. The test stand included all of the components necessary to condition the fluid and measure the critical parameters during a pump contaminant wear test. Two different flow measuring units are provided in this test stand. When the filtering system has been valved into the main system, the flow is monitored by a factory calibrated turbine flow meter (readout not shown). However, when contaminant is injected and the filter are out of the test system flow is measured by an area type flow meter. Thus the precision turbine meter is protected from the heavily contaminated fluid.

The test pumps were driven by an electric motor connected through a sheeve-belt-jackshaft arrangement. The electric motor and required starter can be seen in Figure 25. Figure 26 shows a test pump mounted on the drive unit and connected to the jackshaft. Therefore, the test stand and drive system formed separate facilities which were only connected through the outlet and inlet lines of the pump. The speed of the pump was varied by interchanging various pulleys and thus remained extremely constant during a given test.

The Ferrographic system is shown in Figures 27 and 28. The component shown in Figure 27 is the slide ferrograph of the Ferrograph analyzer as it is called by the manufacturer. Actually the device shown consists of two parts, only one of which was used during this effort.

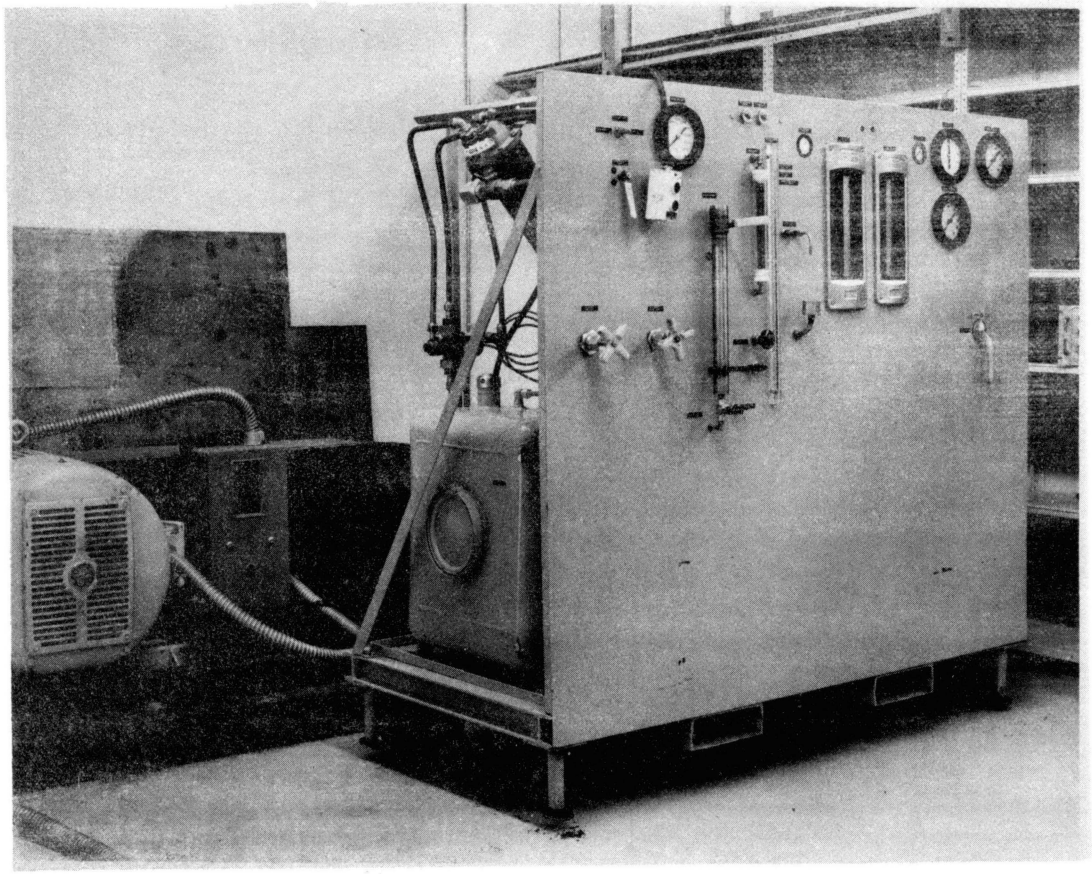

Figure 25. Pump Contaminant Wear Test Stand and Drive

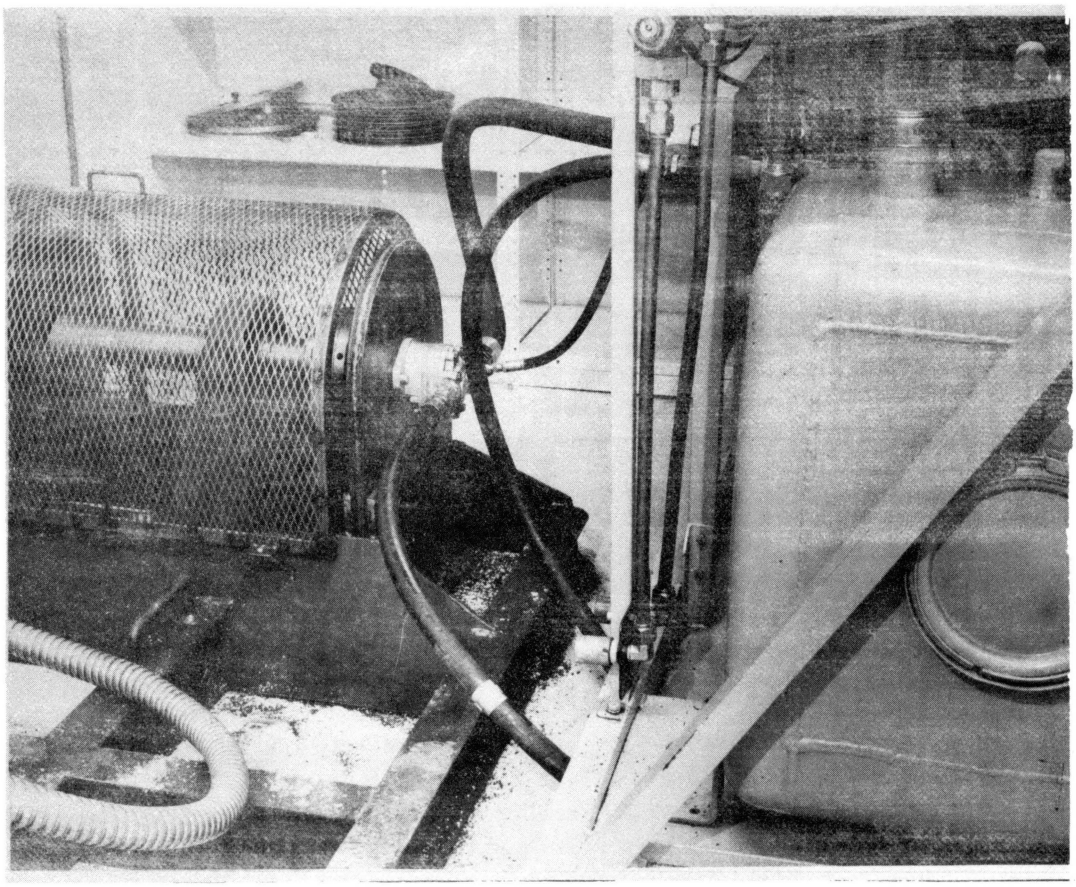

Figure 26. Illustration of Pump Ready for Test

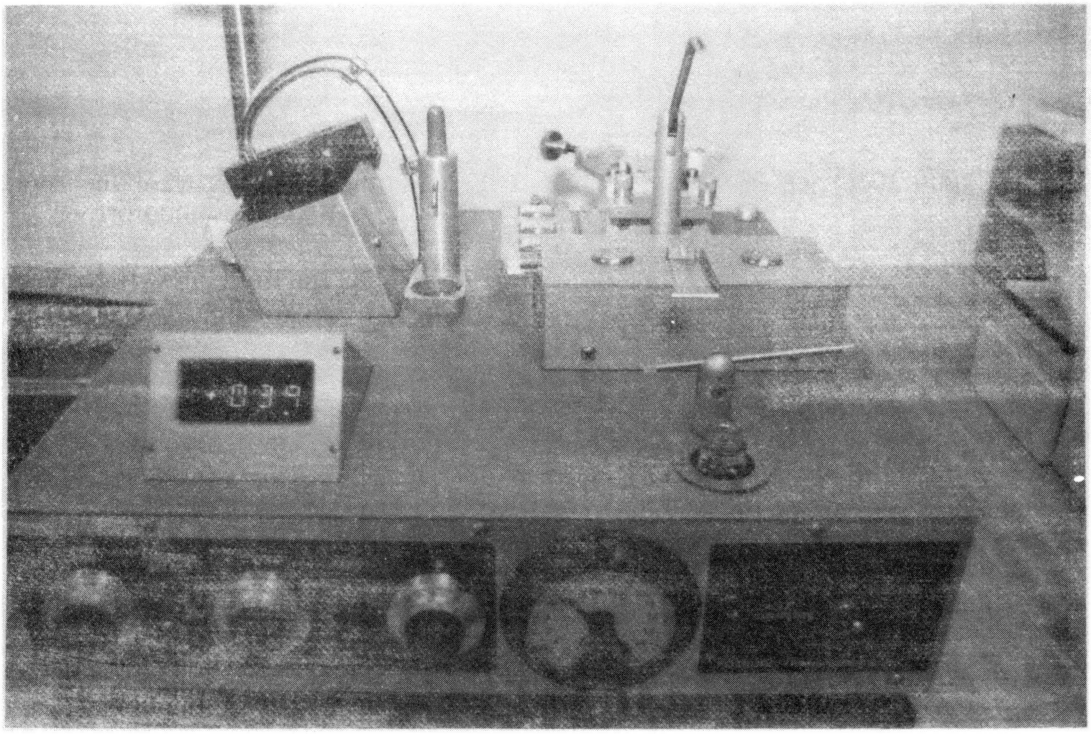

Figure 27. Slide Ferrograph

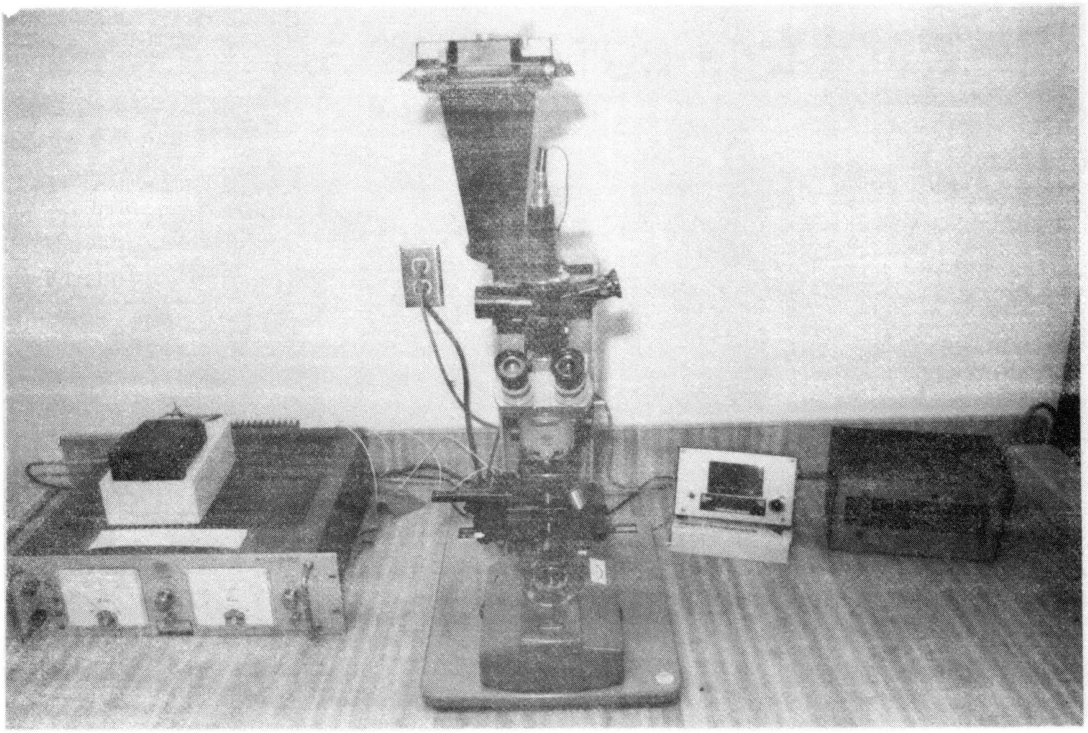

Figure 28. Optical Densitometer

The left hand half of the equipment shown in Figure 27 is a Direct Reading Ferrograph designed to provide density data without the necessity of making a Ferrogram. This device, however, was found to produce considerable data scatter and poor repeatability, probably due to an inadequate power supply. Therefore, the Direct Reading Ferrograph was not used. The right hand half of the piece of equipment was used to produce the Ferrograms utilized in this study.

Figure 28 shows, pictorially, the optical densitometer which is incorporated into a Bichromatic microscope. The light source utilized by the densitometer is an intergral part of the microscope and thus can not be discerned in the figure. The photo cell is shown in the upper portion of Figure 28 and can be identified by the lead wire running from it. The digital voltmeter or readout which measures the output of the photo cell is shown in the extreme lower right hand corner of the figure.

# APPENDIX C

## PUMP CONTAMINANT WEAR TEST AND DESCRIPTION OF CLASSIFIED TEST DUST

The following procedure was followed in conducting the contaminant wear tests for the research investigation. Essentially, this procedure is the same as the pump contaminant sensitivity test (49). The only major exceptions are that the contamination level used was not always the 300 milligrams per litre called out in the standard and all pumps were subjected to a break in procedure at 2500 RPM and 2500 psi. The standard specifies that the break in be conducted at the conditions of the test. Many of the steps given in the following procedure were excerpted directly from the standard test (49).

1.0 PREPARATION OF TEST EQUIPMENT

1.1 Install a pump which is known to be relatively insensitive to contamination in the test circuit.

1.2 Adjust the system volume so that it equals one-fourth (± 10 percent) of the lowest volume flow rate to be used for testing.

1.3 Circulate fluid thru the filter until the contaminant background is less than 10 mg/ℓ.

1.4 By-pass the filter.

1.5 Add AC Fine Test Dust to the system to bring the contamination level to 300 mg/ℓ(± 10 mg/ℓ).

1.6 Inject the contaminant in the form of a well-mixed slurry to prevent agglomeration of particles, ensuring that injection remains uniform over a one minute period.

1.7 Operate the system at the minimum flow rate to be used for testing.

1.8 Extract four fluid samples at 15 minute intervals from the system.

1.9 Measure the gravimetric level of each sample.

1.10 Circulate fluid thru the filter until the contaminant background is less than 10 mg/ℓ.

1.11 Consider the system qualified for testing if the gravimetric levels of clause 1.9, as obtained in clause 1.8's samples, are within ± 10% of the initial gravimetric level requirement of clause 1.5.

2.0 TEST PROCEDURE

2.1 Install the test pump in the circuit.

2.2 Adjust the system volume so that it equals one-fourth (± 10 percent) of the volume flow rate of the pump to be tested, exclusive of the filter cleanup circuit.

2.3 Operate the pump at the 150° F and 2500 RPM with the filter in the circuit. Use the following schedule for the pump operating pressure:

15 minutes at 25% of 2500 psi

15 minutes at 50% of 2500 psi

15 minutes at 75% of 2500 psi

2.4 Operate at 2500 psi until flow rate has remained constant for at least 60 minutes.

2.5 Record the flow rate at the specified pressure and speed as the rated flow of the pump ($Q_r$).

2.6 Determine the quantity of contaminant ($g_i$) required for each injection.

2.7 Prepare a slurry containing $g_i$ grams of contaminant in each of the following size ranges: 0-5, 0-10, 0-20, 0-30, 0-40, 0-50, 0-60, 0-70, and 0-80 micrometres.

2.8 Operate the pump at specified test conditions.

2.9 By-pass the filter.

2.10 Inject the 0-5 μm slurry uniformly over a period of one minute.

2.11 Observe and record the flow rate at two-minute intervals.

2.12 Continue operating until the flow rate becomes constant for 10 minutes or until 30 minutes have elapsed, whichever occurs first.

2.13 Circulate fluid thru the filter for 10 minutes.

2.14 Record the final flow rate for the injection with the pump operating at specified test conditions. If the flow rate has decreased to less than 70% of its original rated value ($Q_r$), the test can be terminated.

2.15 Repeat clauses 2.9 up to and including 2.14 using 0-10, 0-20, 0-30, 0-40, 0-50, 0-60, 0-70, and 0-80 μm contaminant in progressively increasing sizes.

## DESCRIPTION OF CLASSIFIED TEST DUST

The classified test dust specified in this recommended standard is to be obtained by a recognized commercial classifier using AC Fine Test Dust as the base stock. Operate the classifier in accordance with the manufacturer's recommendations. The amount (by weight) of dust collected in the classified fraction at the end of the classification procedure is to be within the following limits:

| Classified Size (μm) | Weight Percentage of Classified Fraction Relative to Full Distribution of AC Fine Test Dust | | |
|---|---|---|---|
| | Minimum % | Average % | Maximum % |
| 0-5 | 36.0 | 39.0 | 42.0 |
| 0-10 | 54.0 | 57.0 | 60.0 |
| 0-20 | 70.0 | 73.0 | 76.0 |
| 0-30 | 82.2 | 85.2 | 88.2 |
| 0-40 | 88.0 | 91.0 | 94.0 |
| 0-50 | 91.0 | 94.0 | 97.0 |
| 0-60 | 93.0 | 96.0 | 99.0 |
| 0-70 | 94.2 | 97.2 | 100.0 |
| 0-80 | 95.0 | 98.0 | 100.0 |

# APPENDIX D

# FLOW DEGRADATION DATA

TABLE X

OUTPUT FLOW RESULTS FROM CONTAMINANT WEAR TESTS

| Speed (RPM) | Pressure (psi) | Cont.Level mg/l | $Q_i$ (GPM) | Output Flow after Indicated Exposure (GPM) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | 0-5 | 0-10 | 0-20 | 0-30 | 0-40 | 0-50 | 0-60 | 0-70 | 0-80 |
| 1500 | 1500 | 20 | 7.99 | 7.99 | 7.99 | 7.99 | 7.99 | 7.96 | 7.92 | 7.84 | 7.80 | 7.61 |
| | 2000 | 20 | 8.30 | 8.30 | 8.30 | 8.30 | 8.30 | 8.26 | 8.22 | 8.15 | 8.11 | 7.99 |
| | 2500 | 20 | 7.65 | 7.65 | 7.65 | 7.65 | 7.65 | 7.54 | 7.46 | 7.35 | 7.12 | 7.04 |
| 2000 | 1500 | 20 | 10.57 | 10.57 | 10.57 | 10.57 | 10.41 | 10.34 | 10.30 | 10.22 | 10.15 | 10.03 |
| | | 20 | 11.44 | 11.44 | 11.44 | 11.44 | 11.44 | 11.41 | 11.37 | 11.33 | 11.15 | 11.04 |
| | | 20 | 11.29 | 11.29 | 11.29 | 11.29 | 11.29 | 11.25 | 11.21 | 11.18 | 11.14 | 11.10 |
| | | 150 | 11.40 | 11.40 | 11.40 | 11.25 | 10.68 | 9.88 | 9.16 | 8.21 | 7.53 | 7.34 |
| | 2000 | 0 | 11.25 | 11.25 | 11.25 | 11.25 | 11.25 | 11.25 | 11.25 | 11.25 | 11.25 | 11.25 |
| | | 10 | 11.25 | 11.25 | 11.25 | 11.25 | 11.25 | 11.25 | 11.25 | 11.21 | 11.18 | 11.10 |
| | | 20 | 11.10 | 11.10 | 11.10 | 11.10 | 11.10 | 11.10 | 10.95 | 10.87 | 10.80 | 10.64 |
| | | 20 | 11.06 | 11.06 | 11.06 | 11.06 | 10.99 | 10.91 | 10.83 | 10.80 | 10.70 | 10.64 |
| | | 20 | 10.76 | 10.76 | 10.76 | 10.76 | 10.72 | 10.68 | 10.64 | 10.57 | 10.53 | 10.45 |
| | | 25 | 12.32 | 12.32 | 12.32 | 12.32 | 12.28 | 12.16 | 12.05 | 11.90 | 11.78 | 11.59 |
| | | 75 | 11.82 | 11.82 | 11.82 | 11.78 | 11.59 | 11.25 | 10.87 | 10.45 | 10.03 | 9.43 |
| | | 150 | 12.28 | 12.28 | 12.28 | 12.16 | 11.59 | 10.87 | 10.34 | 9.39 | 8.74 | 8.02 |
| | | 300 | 12.51 | 12.51 | 12.47 | 12.09 | 10.95 | 10.15 | 9.35 | 7.7 | | |
| | | 300 | 12.39 | 12.39 | 12.35 | 11.78 | 10.83 | 9.01 | 8.25 | 6.8 | | |
| | 2500 | 20 | 10.72 | 10.72 | 10.72 | 10.72 | 10.72 | 10.57 | 10.45 | 10.26 | 10.15 | 9.54 |
| | | 20 | 11.48 | 11.48 | 11.48 | 11.48 | 11.48 | 11.48 | 11.40 | 11.29 | 11.10 | 10.95 |
| | | 20 | 11.56 | 11.56 | 11.56 | 11.56 | 11.52 | 11.37 | 11.21 | 11.10 | 10.95 | 10.83 |
| | | 150 | 11.80 | 11.80 | 11.80 | 11.71 | 11.18 | 10.34 | 9.39 | 8.46 | 7.73 | 7.50 |
| 2500 | 1500 | 20 | 15.12 | 15.12 | 15.12 | 15.12 | 15.09 | 15.05 | 14.97 | 14.93 | 14.86 | 14.78 |
| | 2000 | 20 | 14.32 | 14.32 | 14.32 | 14.32 | 14.21 | 14.13 | 13.98 | 13.87 | 13.64 | 13.49 |
| | 2500 | 20 | 14.70 | 14.70 | 14.70 | 14.70 | 14.67 | 14.59 | 14.40 | 14.32 | 14.10 | 13.94 |

TABLE XI

FLOW DEGRADATION RESULTS FROM CONTAMINANT WEAR TESTS

| Speed (RPM) | Pressure | Cont. Level mg/l | $Q_i$ (GPM) | Flow Degradation after indicated exposure (GPM) $Q_f - Q_i$ | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | 0-5 | 0-10 | 0-20 | 0-30 | 0-40 | 0-50 | 0-60 | 0-70 | 0-80 |
| 1500 | 1500 | 20 | 7.99 | 0 | 0 | 0 | 0 | 0.03 | 0.07 | 0.15 | 0.19 | 0.38 |
| | 2000 | 20 | 8.30 | 0 | 0 | 0 | 0 | 0.04 | 0.08 | 0.15 | 0.19 | 0.31 |
| | 2500 | 20 | 7.65 | 0 | 0 | 0 | 0 | 0.11 | 0.19 | 0.30 | 0.53 | 0.61 |
| 2000 | 1500 | 20 | 10.57 | 0 | 0 | 0 | 0.16 | 0.23 | 0.27 | 0.35 | 0.42 | 0.54 |
| | | 20 | 11.44 | 0 | 0 | 0 | 0 | 0.03 | 0.07 | 0.11 | 0.29 | 0.40 |
| | | 20 | 11.29 | 0 | 0 | 0 | 0 | 0.04 | 0.08 | 0.11 | 0.15 | 0.19 |
| | | 150 | 11.40 | 0 | 0 | 0.15 | 0.72 | 1.52 | 2.24 | 3.19 | 3.87 | 4.06 |
| | 2000 | 0 | 11.25 | 0 | 0 | 0 | 0 | 0 | 0.04 | 0 | 0 | 0 |
| | | 10 | 11.25 | 0 | 0 | 0 | 0 | 0 | 0 | 0.04 | 0.07 | 0.15 |
| | | 20 | 11.10 | 0 | 0 | 0 | 0 | 0 | 0.15 | 0.23 | 0.30 | 0.46 |
| | | 20 | 11.06 | 0 | 0 | 0 | 0.07 | 0.15 | 0.23 | 0.26 | 0.36 | 0.42 |
| | | 20 | 10.76 | 0 | 0 | 0 | 0.04 | 0.08 | 0.12 | 0.19 | 0.23 | 0.31 |
| | | 25 | 12.32 | 0 | 0 | 0 | 0.04 | 0.16 | 0.27 | 0.42 | 0.54 | 0.73 |
| | | 75 | 11.82 | 0 | 0 | 0.04 | 0.23 | 0.57 | 0.95 | 1.37 | 1.79 | 2.39 |
| | | 150 | 12.28 | 0 | 0 | 0.12 | 0.69 | 1.41 | 1.94 | 2.89 | 3.54 | 4.26 |
| | | 300 | 12.51 | 0 | 0.04 | 0.42 | 1.56 | 2.36 | 3.16 | 4.81 | | |
| | | 300 | 12.39 | 0 | 0.04 | 0.61 | 1.56 | 3.38 | 4.14 | 5.59 | | |
| | 2500 | 20 | 10.72 | 0 | 0 | 0 | 0 | 0.15 | 0.27 | 0.46 | 0.57 | 1.18 |
| | | 20 | 11.48 | 0 | 0 | 0 | 0 | 0 | 0.08 | 0.19 | 0.38 | 0.53 |
| | | 20 | 11.56 | 0 | 0 | 0 | 0.04 | 0.19 | 0.35 | 0.46 | 0.61 | 0.73 |
| | | 150 | 11.80 | 0 | 0 | 0.09 | 0.62 | 1.42 | 2.41 | 3.34 | 4.07 | 4.30 |
| 2500 | 1500 | 20 | 15.12 | 0 | 0 | 0 | 0.03 | 0.07 | 0.15 | 0.19 | 0.26 | 0.34 |
| | 2000 | 20 | 14.32 | 0 | 0 | 0 | 0.11 | 0.19 | 0.34 | 0.45 | 0.68 | 0.83 |
| | 2500 | 20 | 14.70 | 0 | 0 | 0 | 0.03 | 0.11 | 0.30 | 0.38 | 0.60 | 0.76 |

TABLE XII

FLOW DEGRADATION RATIO RESULTS FROM CONTAMINANT WEAR TESTS

| Speed (RPM) | Pressure (psi) | Cont. Level mg/l | $Q_i$ (GPM) | Flow Degradation Ratio after Indicated Exposure ($Q_f/Q_i$) 0-5 | 0-10 | 0-20 | 0-30 | 0-40 | 0-50 | 0-60 | 0-70 | 0-80 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1500 | 20 | 7.99 | 1.0 | 1.0 | 1.0 | 1.0 | .996 | .991 | .981 | .976 | .952 |
| | 2000 | 20 | 8.30 | 1.0 | 1.0 | 1.0 | 1.0 | .995 | .991 | .982 | .977 | .963 |
| | 2500 | 20 | 7.65 | 1.0 | 1.0 | 1.0 | 1.0 | .985 | .975 | .960 | .930 | .920 |
| 2000 | 1500 | 20 | 10.57 | 1.0 | 1.0 | 1.0 | .985 | .978 | .974 | .967 | .960 | .950 |
| | | 20 | 11.44 | 1.0 | 1.0 | 1.0 | 1.0 | .997 | .994 | .990 | .975 | .965 |
| | | 20 | 11.29 | 1.0 | 1.0 | 1.0 | 1.0 | .996 | .993 | .990 | .987 | .983 |
| | | 150 | 11.40 | 1.0 | 1.0 | .987 | .937 | .867 | .803 | .720 | .660 | .643 |
| | 2000 | 0 | 11.25 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |
| | | 10 | 11.25 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | .996 | .994 | .987 |
| | | 20 | 11.10 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | .986 | .979 | .973 | .959 |
| | | 20 | 11.06 | 1.0 | 1.0 | 1.0 | .994 | .986 | .979 | .976 | .967 | .962 |
| | | 20 | 10.76 | 1.0 | 1.0 | 1.0 | .996 | .993 | .989 | .982 | .979 | .971 |
| | | 25 | 12.32 | 1.0 | 1.0 | 1.0 | .997 | .987 | .978 | .966 | .956 | .941 |
| | | 75 | 11.82 | 1.0 | 1.0 | .997 | .981 | .952 | .920 | .884 | .849 | .798 |
| | | 150 | 12.28 | 1.0 | 1.0 | .990 | .944 | .885 | .842 | .765 | .712 | .653 |
| | | 300 | 12.51 | 1.0 | .997 | .966 | .875 | .811 | .747 | .616 | | |
| | | 300 | 12.39 | 1.0 | .997 | .952 | .874 | .727 | .666 | .549 | | |
| | 2500 | 20 | 10.72 | 1.0 | 1.0 | 1.0 | 1.0 | .986 | .975 | .957 | .947 | .890 |
| | | 20 | 11.48 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | .993 | .983 | .967 | .954 |
| | | 20 | 11.56 | 1.0 | 1.0 | 1.0 | .997 | .984 | .970 | .960 | .947 | .937 |
| | | 150 | 11.80 | 1.0 | 1.0 | .992 | .947 | .876 | .796 | .717 | .655 | .636 |
| 2500 | 1500 | 20 | 15.12 | 1.0 | 1.0 | 1.0 | .998 | .995 | .990 | .987 | .983 | .978 |
| | 2000 | 20 | 14.32 | 1.0 | 1.0 | 1.0 | .992 | .987 | .976 | .969 | .953 | .942 |
| | 2500 | 20 | 14.70 | 1.0 | 1.0 | 1.0 | .998 | .993 | .980 | .974 | .959 | .948 |

# APPENDIX E

## FERROGRAPHIC DENSITY DATA

TABLE XIII

SUMMARY OF FERROGRAPHIC DENSITY DATA

| | | | | | Ferrographic Density Data after Indicated Exposure (D54/ml) | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Speed (RPM) | Pressure (psi) | Cont.Level mg/l | $Q_i$ (GPM) | 0-5 | 0-10 | 0-20 | 0-30 | 0-40 | 0-50 | 0-60 | 0-70 | 0-80 |
| 1500 | 1500 | 20 | 7.99 | 0.83 | 1.72 | 3.15 | 5.05 | 7.17 | 9.22 | 12.95 | 15.67 | 18.34 |
| | 2000 | 20 | 8.30 | 1.05 | 3.03 | 5.83 | 8.31 | 12.88 | 16.71 | 20.44 | 24.37 | 28.64 |
| | 2500 | 20 | 7.65 | 0.98 | 2.96 | 5.71 | 9.43 | 13.66 | 17.39 | 22.09 | 27.19 | 31.06 |
| 2000 | 1500 | 20 | 10.57 | 1.09 | 2.38 | 3.94 | 5.81 | 8.03 | 10.84 | 13.78 | 17.08 | 20.78 |
| | | 20 | 11.44 | 1.40 | 2.64 | 5.07 | 8.17 | 10.95 | 13.58 | 15.80 | 18.80 | 22.43 |
| | | 20 | 11.29 | 1.42 | 3.04 | 5.66 | 7.83 | 11.23 | 13.86 | 16.76 | 19.83 | 22.46 |
| | | 150 | 11.40 | 7.95 | 16.85 | 44.85 | 88.52 | 120.85 | 155.18 | 206.85 | 254.52 | 294.85 |
| | 2000 | 0 | 11.25 | 0.50 | 1.15 | 1.63 | 2.18 | 2.74 | 3.23 | 3.61 | 3.89 | 4.22 |
| | | 10 | 11.25 | 1.11 | 2.52 | 4.33 | 6.04 | 7.53 | 9.24 | 11.44 | 13.27 | 15.22 |
| | | 20 | 11.10 | 1.30 | 3.23 | 4.83 | 7.14 | 9.76 | 11.99 | 16.61 | 19.81 | 24.16 |
| | | 20 | 11.06 | 0.91 | 2.24 | 4.61 | 7.86 | 11.39 | 16.06 | 19.83 | 24.46 | 27.89 |
| | | 20 | 10.76 | 1.34 | 2.87 | 4.84 | 7.41 | 10.41 | 13.71 | 16.28 | 19.91 | 24.54 |
| | | 25 | 12.32 | 1.75 | 4.28 | 8.21 | 11.46 | 16.13 | 19.58 | 24.35 | 28.20 | 34.40 |
| | | 75 | 11.82 | 3.85 | 7.52 | 12.95 | 21.32 | 33.32 | 44.92 | 56.52 | 68.52 | 78.52 |
| | | 150 | 12.28 | 8.4 | 19.0 | 47.67 | 77.17 | 118.34 | 141.17 | 174.47 | 201.30 | 236.63 |
| | | 300 | 12.51 | 25.0 | 48.50 | 81.0 | 139.83 | 202.50 | 318.33 | 392.5 | | |
| | | 300 | 12.39 | 13.4 | 37.0 | 93.0 | 165.0 | 234.33 | 291.0 | 359.67 | | |
| | 2500 | 20 | 10.72 | 1.42 | 3.12 | 4.43 | 6.74 | 11.12 | 17.89 | 24.93 | 31.10 | 37.57 |
| | | 20 | 11.48 | 1.42 | 3.70 | 8.38 | 12.53 | 17.10 | 22.13 | 27.70 | 34.43 | 39.70 |
| | | 20 | 11.56 | 1.94 | 3.47 | 5.95 | 9.15 | 13.15 | 16.65 | 19.22 | 23.19 | 28.32 |
| | | 150 | 11.80 | 5.0 | 19.8 | 51.8 | 86.8 | 151.47 | 202.8 | 272.47 | 333.14 | 415.14 |
| 2500 | 1500 | 20 | 15.12 | 1.20 | 2.73 | 5.01 | 7.33 | 10.01 | 14.08 | 18.61 | 21.54 | 25.11 |
| | 2000 | 20 | 14.32 | 0.93 | 2.55 | 3.97 | 6.02 | 9.55 | 14.15 | 17.15 | 22.42 | 25.99 |
| | 2500 | 20 | 14.70 | 1.68 | 3.91 | 6.81 | 11.21 | 16.74 | 21.41 | 28.11 | 36.52 | - |

# APPENDIX F

## STATISTICAL ANALYSIS CALCULATIONS

The statistical arrangements of the tests in the research investigation permit evaluation of three parameters. Since more than one test was conducted on a given pump a latin square arrangement was included to appraise the influence of repeated testing on a single pump. In addition, a factorially arranged segment of the test plan allows assessment of the statistical significance of both pressure and speed. Since both flow degradation and Ferrographic data was collected, statistical analysis can be performed on both sets of data. Furthermore, consideration of the data will reveal that the most effect of any variable included in the test plan will be at the 0-80 micrometre particle size range exposure. That is if a variable indicates a non-significant influence at 0-80, it will be even less significant at small size ranges.

# TEST SEQUENCE

## FLOW DEGRADATION RATIO AT 0-80

| PRESSURE (PSI) | TEST NO.1 | TEST NO.2 | TEST NO3 | |
|---|---|---|---|---|
| 1500 | 0.965 | 0.983 | 0.950 | 2.898 |
| 2000 | 0.959 | 0.962 | 0.971 | 2.892 |
| 2500 | 0.939 | 0.890 | 0.954 | 2.783 |
| | 2.863 | 2.835 | 2.875 | 8.573 |

| PUMPS | 300 | 306 | 308 |
|---|---|---|---|
| | 2.799 | 2.881 | 2.893 |

$$C.F. = \frac{(8.573)^2}{3^2} = 8.166$$

$$\text{TOTAL} = (.965)^2 + (.983)^2 + \cdots + (.890)^2 + (.954)^2 - C.F.$$

$$= .006$$

$$\text{ROW(PRESS)} = \tfrac{1}{3}[2.898^2 + 2.892^2 + 2.783^2] - C.F. = .003$$

$$\text{COLUMN(SEQ)} = \tfrac{1}{3}[2.863^2 + 2.835^2 + 2.875^2] - C.F. = .00054$$

$$\text{PUMP} = \tfrac{1}{3}[2.799^2 + 2.881^2 + 2.898^2] - C.F. = .002$$

## ANALYSIS OF VARIANCE

| SOURCE | D.F | S.S | M.S | $F_c$ | $F_T$(5%) |
|---|---|---|---|---|---|
| ROW(PRESS) | 2 | .003 | .0015 | 6.52 | |
| COLUMN (SEQ) | 2 | .00054 | .00027 | 1.17 | 19.0 |
| PUMP | 2 | .002 | .0010 | 4.35 | |
| ERROR | 2 | .00046 | .00023 | | |

SEQUENCE IS NOT SIGNIFICANT AT THE 5% LEVEL

# TEST SEQUENCE

## FERROGRAPHIC DENSITY DATA ~ 0-80

| PRESSURE (PSI) | TEST NO 1 | TEST NO. 2 | TEST NO. 3 | |
|---|---|---|---|---|
| 1500 | 22.43 | 22.46 | 20.78 | 65.67 |
| 2000 | 24.16 | 27.89 | 24.54 | 76.59 |
| 2500 | 28.32 | 37.57 | 39.70 | 107.59 |
| | 74.91 | 87.92 | 85.02 | 247.85 |

| PUMPS | 300 | 306 | 308 |
|---|---|---|---|
| | 82.51 | 90.02 | 75.82 |

$$C.F. = \frac{(247.85)^2}{3^2} = 6825.514$$

$$TOTAL = (22.43)^2 + (22.46)^2 + \cdots + (37.57)^2 + (39.7)^2$$
$$= 367.238$$

$$\text{ROW (PRESS)} = \tfrac{1}{3}[65.67^2 + 76.59^2 + 105.59^2] - C.F. = 283.761$$
$$\text{COLUMN (SEQ)} = \tfrac{1}{3}[74.91^2 + 87.92^2 + 85.02^2] - C.F. = 31.097$$
$$\text{PUMPS} = \tfrac{1}{3}[82.51^2 + 90.02^2 + 75.82^2] - C.F. = 36.020$$

## ANALYSIS OF VARIANCE

| SOURCE | D.F. | S.S. | M.S. | $F_c$ | $F_T$ (5%) |
|---|---|---|---|---|---|
| ROW (PRESS) | 2 | 283.761 | 141.88 | 17.34 | |
| COLUMN (SEQ) | 2 | 31.097 | 15.55 | 1.90 | 19.0 |
| PUMPS | 2 | 36.020 | 18.01 | 2.20 | |
| ERROR | 2 | 16.360 | 8.18 | | |

SEQUENCE IS NOT SIGNIFICANT AT THE 5% LEVEL

# SPEED AND PRESSURE
## w/ SEQUENCE AVERAGED
## FLOW DEGRADATION RATIO ~ 0-80

| PRESS \ SPEED | 1500 | 2000 | 2500 | |
|---|---|---|---|---|
| 1500 | 0.952 | 0.966 | 0.978 | 2.896 |
| 2000 | 0.963 | 0.964 | 0.942 | 2.869 |
| 2500 | 0.920 | 0.927 | 0.948 | 2.795 |
| | 2.835 | 2.857 | 2.868 | 8.560 |

$$C.F. = \frac{(8.560)^2}{9} = 8.1415$$

$$TOTAL = (0.952)^2 + (0.966)^2 + \cdots + (0.927)^2 + (0.948)^2 - C.F.$$
$$= .003$$

$$ROW\ (PRESS) = \tfrac{1}{3}[2.896^2 + 2.869^2 + 2.795^2] - C.F. = .0018$$

$$COLUMN\ (SPEED) = \tfrac{1}{3}[2.835^2 + 2.857^2 + 2.868^2] - C.F. = .0002$$

## ANALYSIS OF VARIANCE

| SOURCE | D.F. | S.S | M.S | $F_c$ | $F_t(5\%)$ |
|---|---|---|---|---|---|
| ROW (PRESS) | 2 | .0018 | .0009 | 3.6 | |
| COLUMN (SPEED) | 2 | .0002 | .0001 | 0.4 | 6.94 |
| ERROR | 4 | .0010 | .00025 | | |

SPEED IS NOT SIGNIFICANT
AT THE 5% LEVEL

# SPEED AND PRESSURE
## w/ SEQUENCE AVERAGED

## FERROGRAPHIC DENSITY DATA ~ 0-80

| Press \ Speed | 1500 | 2000 | 2500 | |
|---|---|---|---|---|
| 1500 | 18.34 | 21.89 | 25.11 | 65.34 |
| 2000 | 28.64 | 25.53 | 25.99 | 80.16 |
| 2500 | 31.06 | 35.20 | 41.38 | 107.64 |
| | 78.04 | 82.62 | 92.48 | 253.14 |

$$C.F. = \frac{(253.14)^2}{9} = 7119.984$$

$$\text{TOTAL} = 18.34^2 + 21.89^2 + \cdots + 35.20^2 + 41.38^2 - C.F.$$

$$= 389.63$$

$$\text{ROW(PRESS)} = \tfrac{1}{3}[65.34^2 + 80.16^2 + 107.64^2] - C.F. = 307.12$$

$$\text{COLUMN(SPEED)} = \tfrac{1}{3}[78.04^2 + 82.62^2 + 92.48^2] - C.F. = 36.32$$

## ANALYSIS OF VARIANCE

| SOURCE | D.F. | SS | M.S | $F_c$ | $F_T$(5%) |
|---|---|---|---|---|---|
| ROW(PRESS) | 2 | 307.12 | 153.56 | 13.29 | 6.94 |
| COLUMN(SPEED) | 2 | 36.32 | 18.16 | 1.57 | 6.94 |
| ERROR | 4 | 46.19 | 11.55 | | |

SPEED IS NOT SIGNIFICANT
AT THE 5% LEVEL

# PRESSURE

## W/SEQUENCE AND SPEED AVERAGED

## FERROGRAPHIC DENSITY DATA ~ 0-80

| 1500 PSI | 2000 PSI | 2500 PSI | |
|---|---|---|---|
| 18.34 | 28.64 | 31.06 | |
| 21.89 | 25.53 | 35.20 | |
| 25.11 | 25.99 | 41.38 | |
| 65.34 | 80.16 | 107.64 | 253.14 |

C.F. = 7119.984

TOTAL = 389.63

TRTSS(PRESS) = 307.12

## ANALYSIS OF VARIANCE

| SOURCE | D.F. | S.S. | M.S | $F_c$ | $F_r$(5%) |
|---|---|---|---|---|---|
| PRESSURE | 2 | 307.12 | 153.56 | 11.16 | 5.14 |
| ERROR | 6 | 82.51 | 13.75 | | |

PRESSURE IS SIGNIFICANT AT THE 5% LEVEL

# PRESSURE

w/ SEQUENCE AND SPEED AVERAGED

FLOW DEGRADATION RATIO ~ 0-80

| 1500psi | 2000psi | 2500psi | |
|---|---|---|---|
| 0.952 | 0.963 | 0.920 | |
| 0.966 | 0.964 | 0.927 | |
| 0.978 | 0.942 | 0.948 | |
| 2.896 | 2.869 | 2.795 | 8.560 |

C.F. = 8.14151

TOTAL = .00288

TRTSS (PRESS) = $\frac{1}{3}[2.896^2 + 2.869^2 + 2.795^2] - C.F. =$

$= .001834$

## ANALYSIS OF VARIANCE

| SOURCE | D.F. | S.S | M.S | $F_c$ | $F_T(5\%)$ |
|---|---|---|---|---|---|
| PRESSURE | 2 | .001834 | .00092 | 5.41 | 5.14 |
| ERROR | 6 | .001050 | .00017 | | |

PRESSURE IS SIGNIFICANT AT THE 5% LEVEL

VITA 2

Richard Kenneth Tessmann

Candidate for the Degree of

Doctor of Philosophy

Thesis: NON-INTRUSIVE ANALYSIS OF CONTAMINANT WEAR IN GEAR PUMPS THROUGH FERROGRAPHY

Major Field: Mechanical Engineering

Biographical:

Personal Data: Born in Solomon, Kansas, May 9, 1938, the son of Mr. and Mrs. S.R. Tessmann. Married in Perry, Oklahoma, February 14, 1958, to Barbara Lavon Gould. Beget Terry Michael Tessmann, June 4, 1959, and Douglas Wayne Tessmann, November 14, 1960.

Education: Graduated from Solomon High School, Solomon, Kansas, in May, 1956; received the Bachelor of Science degree from Oklahoma State University in 1961 with a major in Mechanical Engineering; received the Master of Science degree from Oklahoma State University in 1970, with a major in Mechanical Engineering; completed requirements for the Doctor of Philosophy degree at Oklahoma State University in December, 1977.

Professional Experience: Sales Engineer, Bailey Meter Company, 1961-1963; Research Design Engineer, Cessna Aircraft Company, Fluid Power Division, 1963-1968; Research Associate, Fluid Power Research Center, 1968-1971; Research Engineer and Program Manager, Fluid Power Research Center, 1971-Present; Industrial Consultant, 1968-Present.

Professional and Academic Affiliations: Society of Automotive Engineers, National Fluid Power Association, Phi Kappa Phi.

Publications: More than fifty papers and published research reports in the areas of contamination control, filtration, contaminant wear and Ferrography.