A STUDY OF THE SYNERGISTIC

EFFECTS OF PUMP WEAR

By

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Submitted to the faculty of the
Graduate College of the
Oklahoma State University
in partial fulfillment of
the requirements for
the degree of
DOCTOR OF PHILOSOPHY
December, 1987

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ACKNOWLEDGMENTS

I wish to express my most deep and sincere appreciation to Dr. Ernest C. Fitch, my advisor, for his encouragement, guidance and confidence in me. He has made a major contribution to my career. His support and understanding are forever appreciated.

I also extend my thanks to Dr. Bennett L. Basore, Dr. Ramachandra G. Ramakumar, and Dr. Kenneth E. Case for serving as part of my advisory committee. Their comments and encouragement are greatly appreciated.

I am grateful to Lynn Zimmerman for her patience and willingness to type this dissertation, even at odd times.

My special thanks go to Mr. Vince Amodeo for his help in conducting the experiments and for direction concerning the computer data base. I am also grateful to all members of the FPRC staff for their help and encouragement, especially Mr. Pat Nealon and Mr. Mark Torbett. Also to Ms. Stacy Sanderlin, many thanks for her help in editing this dissertation.

To my wife Melissa, I want to express my gratefulness for her trust, understanding and sacrifice. She quietly provides the major support I need in my career.

I also want to express my gratefulness and thanks to my parents, brothers, and sisters for their love, support and prayers. They are a large part of my success and accomplishments.

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NOMENCLATURE

d_i	particle Size i
d_c	diameter of capillary orifice
$f(P_i)$	function of pump inlet pressure
h	film thickness or clearance
k	empirical constant
m	empirical constant
t	time
s	length
v	velocity
A	empirical constant
A_o	Arrhenius constant
A_t	total area
A_1	empirical constant
B	empirical constant
B_1	emirical constant
C	time constant for abrasive wear
C_i	concentration of particle size i
C_c	time constant for combinatorial model
C_o	time constant
C_w	concentration of wear
C_1	empirical constant
D_1	inner diameter of pocket
D_2	outer diameter of pocket

E_1	empirical constant
E	activation energy
F	force
G	time constant for adhesive wear
H	material hardness
K	wear rate
L	load
L_1	length of capillary orifice
M	mass
N_p	number of particles
P	system pressure
P_I	inlet pressure
P_O	atmospheric pressure
P_r	pocket pressure
P_v	vapor pressure
PPM	parts per million
PPM/OZ	parts of metallic iron present in a million parts that constitutes one ounce mass of fluid
Q	flow rate
R_o	minimum bubble radius
R_m	maximum bubble radius
T	absolute temperature
R	universal constant
V	wear volume
W	load
X	distance
α	proportionality constant

ε	rarefraction coefficient
ρ	density
μ	fluid viscosity
Δ	delta
λ	film thickness to surface ratio
τ_1	relaxation time due to viscosity
τ_2	relaxation time due to shear

CHAPTER I

INTRODUCTION

Several mechanical and chemical processes can occur when two surfaces interact in relative motion in a given environment. The occurrence of these processes normally depends on the nature of motion and the severity of conditions under which the two surfaces are exposed. These mechanical and chemical processes are usually characterized as wear modes, and their presence causes irreversible changes in the two interacting surfaces. In any mechanical system, the changing of two interacting surfaces by one or several wear modes reduces system reliability and service life.

Many types of mechanisms with surfaces interacting under different relative motion can be found in any mechanical system. Factors such as environment and operational practices can not only accelerate any ongoing system wear process but can also create new wear modes. The combined effects of the different wear modes (synergism) on internal mechanisms determine the useful life of a given system. This investigation examines synergistic wear and is the first known attempt to establish synergistic effects of wear modes using a hydraulic pump.

Wear is the phenomenon of material removal by mechanical and/or chemical interactions. In the past, four basic wear mechanisms were commonly considered: adhesion, abrasion, corrosion, and surface fatigue. Other wear mechanisms such as cavitation, erosion, fretting, delamination, hydrogen-induction, electrokinetics and radiation have not been included as main wear categories in the past [1, 2]. The following breakdown of the frequency with which these types of wear are encountered in industrial situations has been given by Eyre [3]: abrasion - 50%, adhesion - 15%, erosion - 8%, fretting - 8%, chemical - 5%, and other - 14%.

Each wear mode can be individually recognized and defined. They can also be rigorously analyzed independently through the basic mechanism of interaction between the surfaces in contact under load and motion. However, in a machine element, the overall wear results from the interdependent operation of several of these mechanisms, either sequentially or simultaneously (synergism).

Hydraulic pumps use a variety of motion to transform mechanical power into hydraulic power. During the energy transformation, each pumping mechanism is subjected to different wear modes. Failure modes in pumps can be easily observed and characterized from the pump operation point of view. These wear modes are the effects of individualistic features strongly influenced by the pump operation mode. Only one of the above-mentioned wear modes, abrasion, has been studied using actual hydraulic pumps. Presently, pump life prediction can only be made under abrasion conditions [4]. There exists no means of predicting the life of a pump operating under multimodal conditions such as cavitation, adhesion, corrosion, fatigue, or other wear modes.

In the field, pumps are subject not only to the abrasion mode (particle contaminant), but also to adhesion (boundary lubrication), cavitation (low inlet pressure), corrosion (water in the system), fatigue (load cycle), and others. Hence, the total wear observed in a pump is the result of complex combinatorial effects of the ongoing wear processes. Realistic pump life predictions thus can be made only if a prediction based upon individualistic wear modes is framed into a synergistic interpretation of the complex wear processes taking place concurrently.

This dissertation examines the synergistic wear produced by the four most common wear modes in actual hydraulic pumps. These modes are cavitation, corrosion, adhesion, and abrasion. Each wear mode is theoretically discussed and validated independently and in combination with other wear modes by the analysis of experimental results obtained using actual pumps. This dissertation also discusses the findings and the insights gained through this research and its application to pump diagnosis and service life prediction.

CHAPTER II

LITERATURE REVIEW

Wear-related literature is quite extensive and diverse, offering conflicting views on wear mode classification, evaluation, and prediction. The wear phenomenon has long been recognized; however, it has been intensively studied only since World War II. Many experimental wear theories and wear test methods have been developed, but no reliable method yet exists for predicting wear in machine components. Part of the problem is that a wide variety of wear failure types present in actual machines have not been studied synergistically.

A thorough search of literature has shown that much investigation has been conducted relating to the study and prediction of various wear modes. However, very little of the existing literature applies these theories to predicting wear in pumps. This section reviews research relating to wear modes, wear analysis, and pump wear forecasting.

Wear Modes

Wear is defined as the unwanted removal of surface material [5]. It can be the result of a variety of processes and can cause different effects, depending upon the specific component affected and its operational requirements. Thus, wear is being investigated from the fundamental point of view of how the dissipative process leads to material removal and from the practical point of view of how wear affects component behavior.

No common classification of wear modes exists since there are no clear-cut factors to be used as a basis for such classification. Kostetskii [6] classified the wear phenomena into oxidation, thermal, abrasive, and pitting processes that occur at the points of contact. Khrushchov [7] proposed five types of wear occurring from abrasion, plastic deformation, brittle failure, adhesion-corrosion, and oxidation. A similar classification is proposed by Burnell and Strang [8], which includes wear due to adhesion, corrosion, abrasion, plowing, and various other causes.

As researchers learned more about the interaction and destruction of surfaces, a new wear classification emerged. Kragelskii [9] proposed a classification on the basis of the degree to which the fatigue processes developed at the point of contact: frictional multi-cycle fatigue, frictional low-cycle fatigue, microcutting, adhesive damage of a friction joint, and cohesive breakaway. Rabinowicz [10] reported that most wear investigations established four main types of wear - adhesion wear, abrasive we, corrosive wear, and surface fatigue- and several secondary processes often classified as independent types of wear - fretting, cavitation, and erosion.

Wear is also classified on the basis of particle separation. Peterson [11] considered ten ways in which wear particles separate. In connection with wear particles, Reda [12] also attempted to classify wear particles based on their shape, size and composition.

In a more recent attempt at classification, Fitch [2] summarized a total of eleven wear modes found in hydraulic systems under three types: surface-to-surface, fluid-to-surface and environment-to-surface. Surface-to-surface modes include abrasion, adhesion, surface fatigue, delamination, and fretting. Erosion, cavitation, corrosion, hydrogen-induction, and electro-kinesis are classified under fluid-to-surface wear. Radiation is considered an environment-to-surface mode. Fitch's classification is aimed at determining the cause of each wear mode or stressing object.

Wear modes in mechanical systems are directly correlated to operating conditions. Most machines are designed to operate under hydrodynamic lubrication, which is thought to minimize the wear process. However, 80 to 90% of machine breakdowns are caused by wear [13]. Eyre [3] lists abrasion wear as causing 50% of the most common failure in industrial machines. In pumps, Feicht [14] found that 70% of the pumps sent for repair showed damage due to contamination in hydraulic fluid, while 10% of the pumps showed damage due to cavitation. Thus, abrasive wear obviously takes place under lubricated conditions due to asperity contact or to loose abrasive particles of size approximately equal to the film thickness.

When considering the wear modes that may occur at a lubricated contact between moving surfaces, as in the case of pumps, two criteria must be taken into account: lubrication and the relative motion between the surfaces [15]. Reynolds [16] first produced the mathematical expression fundamental to all lubrication theory describing the process of film formation between relatively moving surfaces. He lists three parameters -- wedge, stretch, and squeeze -- as contributors that generate the necessary pressure to carry the load known as hydrodynamic lubrication. Three types of lubrication regions are recognized today according to the dimension of the film thickness that separates the moving forces. The lubrication is <u>hydrodynamic</u> if the film is greater than the surface roughness of the moving surface; it is <u>mixed</u> if the film thickness is approximately equal, and it is <u>boundary</u> if no film thickness exists [11, 15]. These lubrication regions are best represented by the well-known Stribeck curve shown in Figure 1 [1, 15]. The Stribeck curve shows the variation of the friction coefficient with the nondimensional Sommerfeld number at different lubrication regions.

Pumps are designed to work under hydrodynamic lubrication. In this lubricated region, wear is expected to be minimal. However, when abrasive particles of a size approximately equal to the pump's internal clearances are present

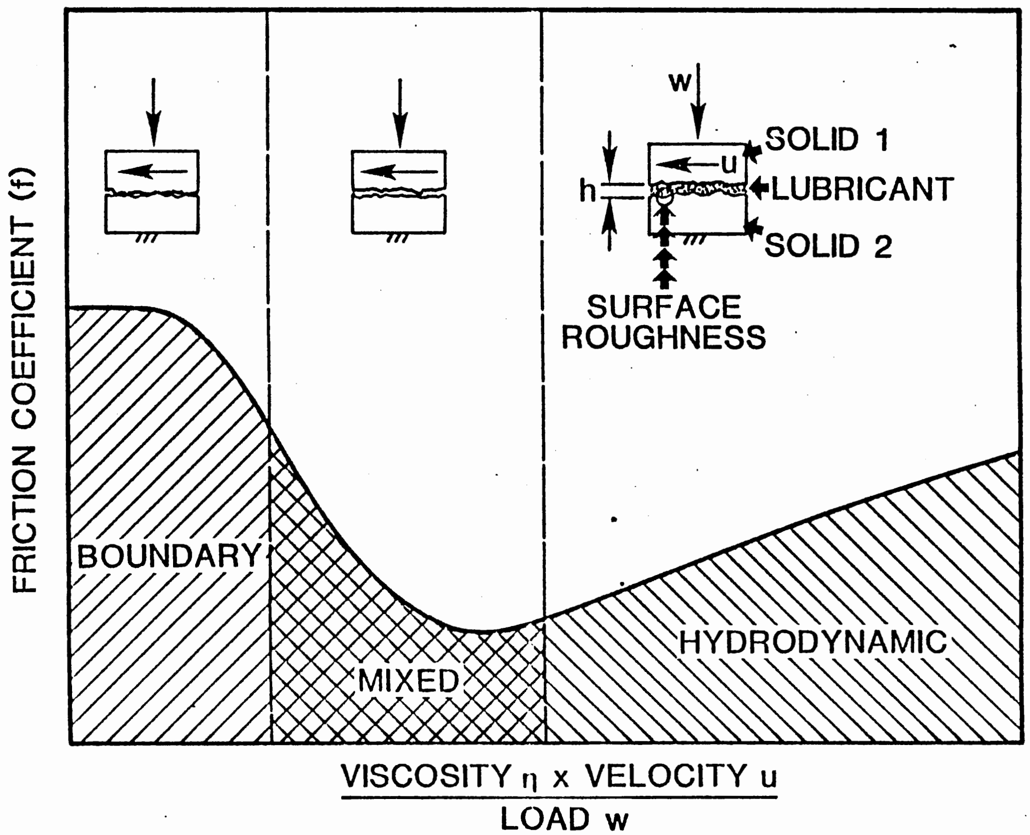


Figure 1. Stribeck curve and lubrication regions

in the fluid, three-body abrasion wear is generated [4]. Hong [17], using a modified Falex machine, investigated the three-body abrasion mechanism. For a specific bearing configuration, Hong found that the wear rate is proportional to the injected particle concentration. Wear in three-body abrasion is also a function of particle size, shape, hardness, material, and lubricant additives -- parameters which are continuously being investigated [18, 19].

If abrasive particles cause the wear, then filtration reduces the wear rate. Hong [17] developed a tribo-filtration model for wear control. However, while filtration controls particle concentration in the fluid, the mechanisms that generate particles in the pump are external to filtration, assuming the filter does not release the captured particles. It is known that particles can actually be generated by pumps. Surprisingly, the effect of these particles on abrasive wear has not yet been studied. However, Fitch [20] recognized particle generation as being either externally ingressed or internally produced. He showed that a piston pump can produce up to 34 mg/h (6.2×10^4) particles greater than 10 microns.

Wear particle size varies depending on the wear mode. Bose [21] and Backe [22] agreed that cavitation wear produces wear particles larger than 20 microns in steels and even larger in softer materials. Beerbower [23] presented a particle size distribution for different wear modes. He found that adhesive wear produces wear particles up to 150 micrometers. Akasaki [24] observed that the wear debris generated in boundary lubrication is less than 15 microns in size. Batchelor [25] discussed the relationship between oxide film and wear. He found that oxides formed over sliding surfaces are approximately 2 to 5 microns in size. Ruff [26] showed that erosion and abrasion also produce particles of 2 to 3 microns in size. Wear particles produced by any of the above-mentioned wear modes are large enough to become abrasive particles and generate abrasion wear in pump clearances.

During the last twenty-five years, the effects of contaminated fluid in pumps have been investigated. Bensch and Fitch [27] developed the theory of contaminant sensitivity of fluid power pumps on the basis of a standard test condition with fixed operating parameters. Abrasive particles of various sizes are injected into the system to maintain the concentration level constant. The abrasive effects are measured in output flow degradation. Ingression rate is not constant in this experiment. In the field, ingression from either external environment or internal environment (wear mode) is usually unknown. Literature is not available concerning the investigation of abrasion effects of internally generated particle contaminants.

Synergistic Wear

Most quantifications of wear involve the observation of two or more interdependent mechanisms of interaction between surfaces in contact under load. These mechanisms sometimes act sequentially and at other times simultaneously [28]. This form of microscopic synergistic wear is recognized by several authors under specific wear classifications [6-8].

Synergism between different wear modes has not been systematically studied. Synergism with corrosion wear is more frequently found in the literature. The synergistic effects of abrasion and corrosion during wear were studied by Noel [29]. He showed that the contribution of corrosion to wear increases with the abrasive load. Abd-El-Kader [30] asserted that corrosive wear requires both corrosion and rubbing. Rubbing can be originated by either adhesion, abrasion, cavitation, erosion, or fatigue. Furthermore, a synergistic effect of corrosion exists with different wear modes [25]. Other types of synergism besides corrosion can also occur. Sasada [31] showed how, depending on the particle size, a transition between abrasive and adhesive wear occurs. This microscopic synergism between interacting mechanisms of abrasive and adhesive wear changes wear rate of specific adhesive wear.

At a macroscopic level, synergism is established on the basis of the effects of particles generated by a specific wear mode or combination of several modes. This synergism, typical in actual machines like pumps, has not yet received any detailed consideration in the literature. Under lubricated conditions, the presence of particles can generate wear modes such as erosion or abrasion [6, 17]. Depending on the wear mode(s) in progress, the generation of particles can change the three-body abrasion rate depending on the particle size, shape, hardness and concentration [17, 18, 19]. Surprisingly, synergism of this kind has not been given appropriate research consideration, perhaps due to its experimental cost and context-specific evaluations.

Summary

Several facts become apparent from this literature review. Research on the abrasive effects of wear generated particles do not exist in the literature. In actual machines like pumps, wear modes should not be examined independently but in conjunction with the effects of wear debris on pump wear (synergism). Wear debris generated by a specific wear mode depends on the severity and exposure time. The abrasive effects of wear debris generated by different wear modes in pumps have not yet been examined. The study of synergistic wear effects of pump wear modes will provide a more realistic view of the actual pump wear process. In addition, it will also allow closer predictions and control of pump service life.

CHAPTER III

SYNERGISTIC EFFECTS OF PUMP WEAR

Generally, many variables affect the wear of a given system. These can be classified into three main groups: operational variables, design variables, and environmental variables [32, 33]. Pressure, speed, temperature, and lubricity are included in the operational variables. Under design variables are materials, motion, and geometrical aspects. In an actual system, these variables simply identify the system or component being analyzed. Environmental variables include humidity, cleanliness, and abrasivity.

The variables affecting wear are often interdependent. These variables are summarized in Fig. 2. For example, the geometry of the system changes depending on the operating pressure level. This effect will make the system somewhat susceptible to environmental effects and consequently to internal state changes (wear). Thus, each system is sensitive in its own way to a given severity level of operation and environmental conditions. The sensitivity of the system or component to internal changes determines its useful life. Using this rationale, components' sensitivity to a given environment can be evaluated using different methods of monitoring internal changes in the system [34].

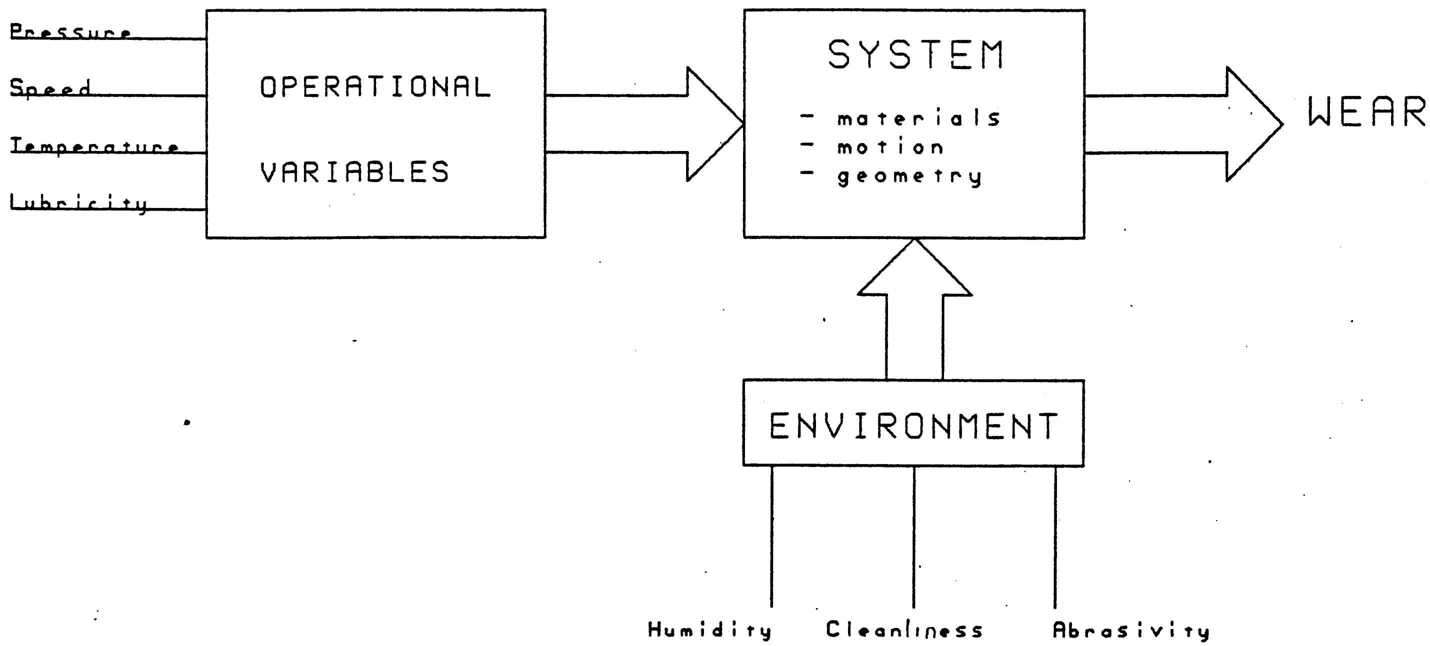


Figure 2. Variables affecting wear.

Often the interdependence between the operational parameter and the system design can simply establish the necessary conditions for the origin of wear. Thus, a system is sensitive to wear modes. In addition, wear modes change the internal environment of the system. A system can often be sensitive to its internal environmental condition (more wear). This latter sensitivity is a synergistic effect of the wear mode denotated here as synergistic wear.

The synergistic effects of four distinctive wear modes are analyzed here. The wear modes are cavitation, corrosion, adhesion and abrasion. These are the most common wear modes in pumps [14, 35]. Although cavitation, adhesion, and corrosion exist independently, their synergy in pumps generates abrasion which occurs when wear particles of a dimension similar to the pump's internal clearances are generated by each of the wear modes and pass through these clearances. For this reason, each wear mode is investigated in conjunction with abrasion wear. This section first examines each of the four wear modes independently. Next, it explains the relationship between pump operating conditions and wear modes. Finally, it proposes a synergistic view of the pump wear process. This information provides the necessary background for the formulation of the synergistic model and the required experiments for the model verification.

Wear Modes

The final product of any wear mode is material which has been removed and is known as wear debris particles. Basically, the difference between wear modes lies in the stressing object triggering the process of material removal [2]. Removal mechanisms are controlled by either or both elastic and plastic deformation [18, 36]. Several removal mechanisms are shared by wear modes on a microscopic level (surface interaction). These removal mechanisms include distribution of over stresses and strains, accumulated damage in the subsurface, initiation and propagation of cracks, and removal of particles. However, for a given wear mode the stressing object is responsible for providing the accelerating factor in the material removal process. The amount of material removed per unit time is defined as the wear rate [1].

Most of the wear rate coefficients for the various wear modes can be derived using the wear law first proposed by Archard [37]. This law states that "the volume of wear materials is proportional to the distance of travel, to the load, and is inversely proportional to the yield stress or the hardness of the softer material." This law is expressed in Eq. (1).

$$V = K \frac{L\ X}{H} \qquad (1)$$

where V = volume of wear

L = load

X = distance

H = material hardness

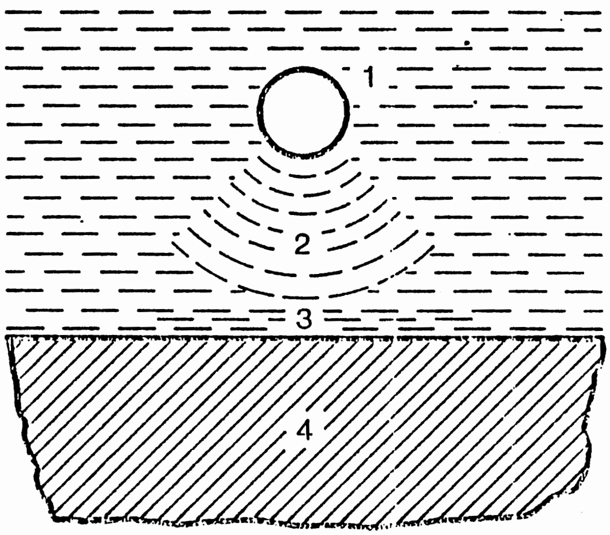
K = proportionality constant

For constant conditions of load, distance , and material hardness, K represents the wear coefficient characteristic of each mode [32]. When examining wear modes, the influence of all factors in equation 1 is analyzed independently. However, in this research each of the four wear modes is first examined on the basis of the stressing factor that primarily affects the volume of wear being generated.

<u>Cavitation Wear</u>

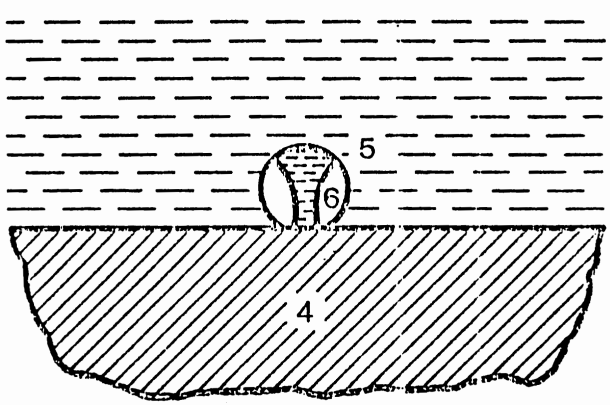
Cavitation is the dynamic process of gas cavity growth and collapse in a liquid [38]. Cavitation wear (or cavitation erosion) is produced by the fatigue action from microjets formed from the implosion of vapor bubbles [39]. The damage produced by the microjets is analogous to soft particle erosion.

Cavitation wear is quite different from other wear modes. The load imposed upon the rubbing surfaces is generated by the cavitation phenomena. Rayleigh [40] proposed that when the vapor bubble collapses, it generates a shock wave which causes the adjacent volumes of fluid to impact against the solid (Figure 3). The impact force is propor-



1-BUBBLE
2-SHOCK WAVE
3-ADJACENT VOLUME OF FLUID
4-SOLID BODY

Figure 3. Collapse of cavitation bubbles [41]



4-SOLID BODY
5-BUBBLE
6-JET

Figure 4. Collapse of cavitation bubbles [42]

tional to the ratio of the bubble contraction radius. However, Cook [41] holds that when a bubble collapses, the liquid acts continuously on the surface of the solid. The impact force is therefore proportional to the bubble contraction velocity. Kornfelds [42] proposed that cavitation damage is produced by the impact of liquid jets. The bubble is forced in on a certain section causing a jet to form. This jet attacks the materials located nearby (Figure 4). However, discrepancies between predicted and observed data are still observed with Kornfeld's theory. Thus in 1980, Kozyrev finally established that cumulative cavitation jets form and produce such rapid effects that the fluid behaves like a solid, with pressures adequate to damage any material.

Cavitation wear depends on many factors. For a given condition of material and fluid velocity, the fluid characteristics are extremely important. Vapor pressure, air content, surface tension, and fluid viscosity are parameters influencing the cavitation phenomenon and so the cavitation wear [39].

Adhesion Wear

Adhesion wear occurs by transference of material from one surface to another during relative motion due to a process of "solid-phase welding" [15]. Adhesion transfer refers to the transfer of material from one body to another through the process of cold welding at the asperity junction

[15]. In a practical sense, the designation "adhesion wear" characterizes cases of wear in which adhesion transfer is the important controlling mechanism. The process of particle formulation in adhesion wear has been extensively investigated. Sasada [43, 44] introduced the mutual transfer and growth theory for wear particle formulation shown in Figure 5. The process described shows the contact of asperities, the breakdown of the junction, and the formation of a transfer element. Adhesion wear particles are created when the transferred material finally breaks. Sasada [45] described the formulation of flake-particles by the "press-slide flattening" process shown in Figure 6.

<u>Corrosion Wear</u>

The corrosion process involves acid-based reactions as well as electrochemical reactions [46]. It is the combination of both these reactions that produces oxide films on metal and acid base reactions on the reactive solution. Corrosion occurs when a surface reacts with its environment (fluid) forming a film (oxide). When two moving objects come into contact with each other, this oxide is removed. Then the surface reacts again, forming a new oxide film [47]. Corrosion wear involves both the chemical reaction and the removal of the reaction product as the consequence of rubbing [15, 47].

When a liquid covers a surface, as in lubricated systems, the film growth (oxidation rate) varies depending

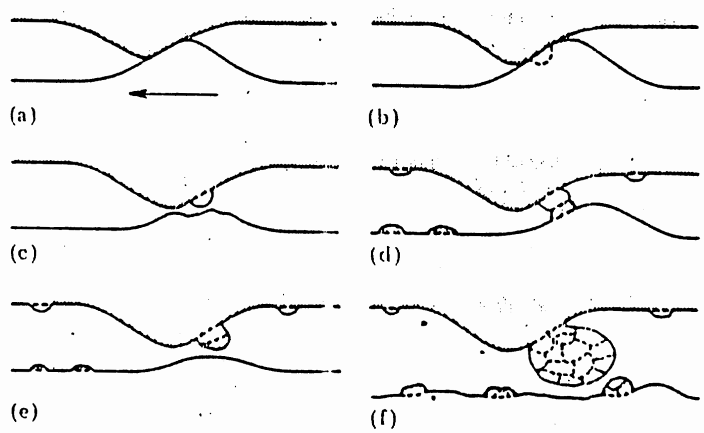


Figure 5. Sasada's model for the formation of a wear particle through a mutual transfer and growth process [44]

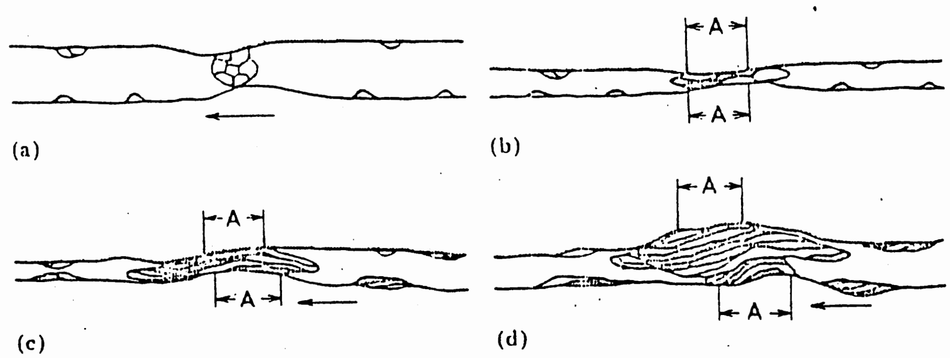


Figure 6. Sasada's model for the press-slide flattening formation of a transfer particle [45]

on the solubility and diffusivity of oxygen in the liquid. However, when oil covers the surface, the oxidation rate is slowed down due to the small diffusivity and solubility of oxygen in oil [25] (Figure 7).

The removal of the reaction products of oxidation occurs by mechanical action such as rubbing or adhesion [25, 30, 47]. The mechanical wear also influences the formation of oxide films. A balance between the formation of oxide films and their destruction by contact controls the corrosion wear process. Progressive destruction of the oxide film by the removal mechanism may accelerate the oxidation rate if cracks in the film allow oxygen to penetrate the film [25, 47].

Abrasion Wear

Abrasion between materials of different hardness occurs when the soft metal surface is plowed by wear particles or hard asperities [2]. Abrasion wear is traditionally divided into two categories: two-body and three-body abrasion. Two-body abrasion takes place when a rough surface or fixed abrasive particle plows across a surface, removing material. Three-body abrasive wear occurs when the abrasive particles are loose and slide across the wearing surface [10] Figure 8. This 3-body mode is encountered in lubricated machines like pumps.

Three-body abrasive wear under the conditions of fluid film lubrication takes place when loose abrasive particles

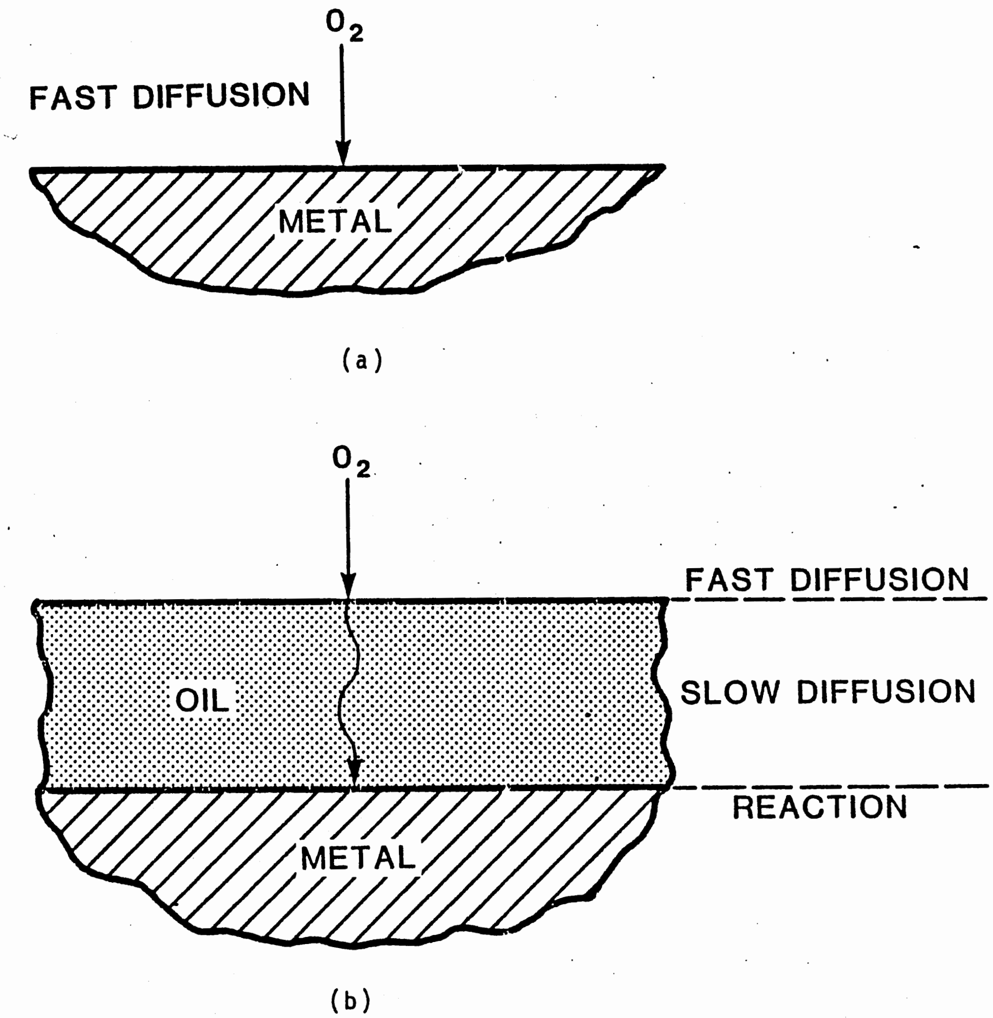


Figure 7. Effects of the surface film on oxygen diffusion: a)oil-free surface; b)surface covered with oil

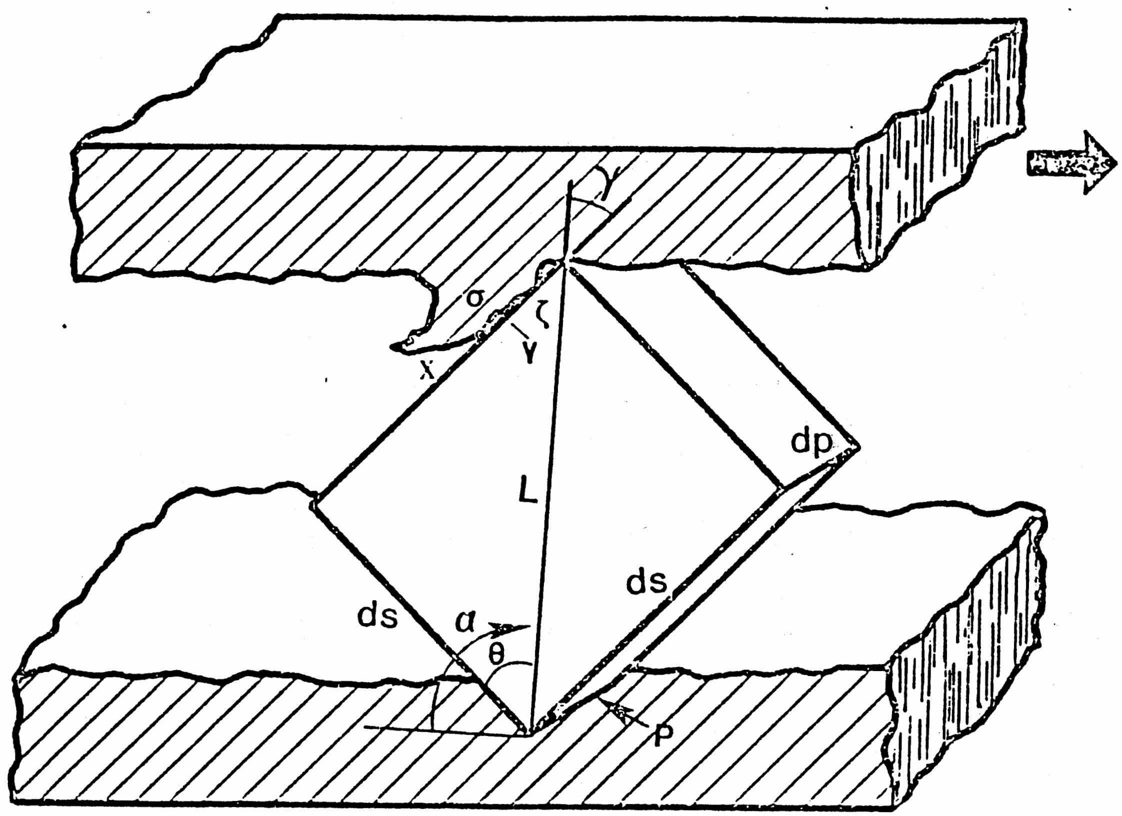


Figure 8. Three-body abrasive wear

or wear debris in the lubricant are larger than the fluid film thickness. The particles and debris then indent and cut the metal surfaces. Several researchers [48, 49, 50] agree that this mechanism includes over-stress of wearing surfaces by the abrasive particles causing indentations, fault at component surfaces, and accelerated fatigue and possible adhesion at the cavity edge. Smaller particles do not indent or cut but merely roll between the surface causing a small amount of erosive wear.

Abrasive wear depends on many factors, such as load, material hardness, abrasive particles, velocity, and film thickness. The nature of the abrasive particles - size, shape, hardness, and toughness - are also very important.

In summary, the nature of the cavitation, adhesion, corrosion and abrasion wear modes has been examined. Each wear mode possesses a trigger factor, or stressing object, which accelerates the wear process. For cavitation wear the stressing object is the impact jet; for adhesive wear, asperity contact; for corrosion wear, oxide film growth or corrosion rate; and for abrasive wear, particle size. The wear process for each mode shares two basic mechanisms - elastic and plastic deformation at different levels. The common characteristic in all wear modes is the final product - wear debris. Figure 9 summarizes the breakdown process of the four wear modes examined.

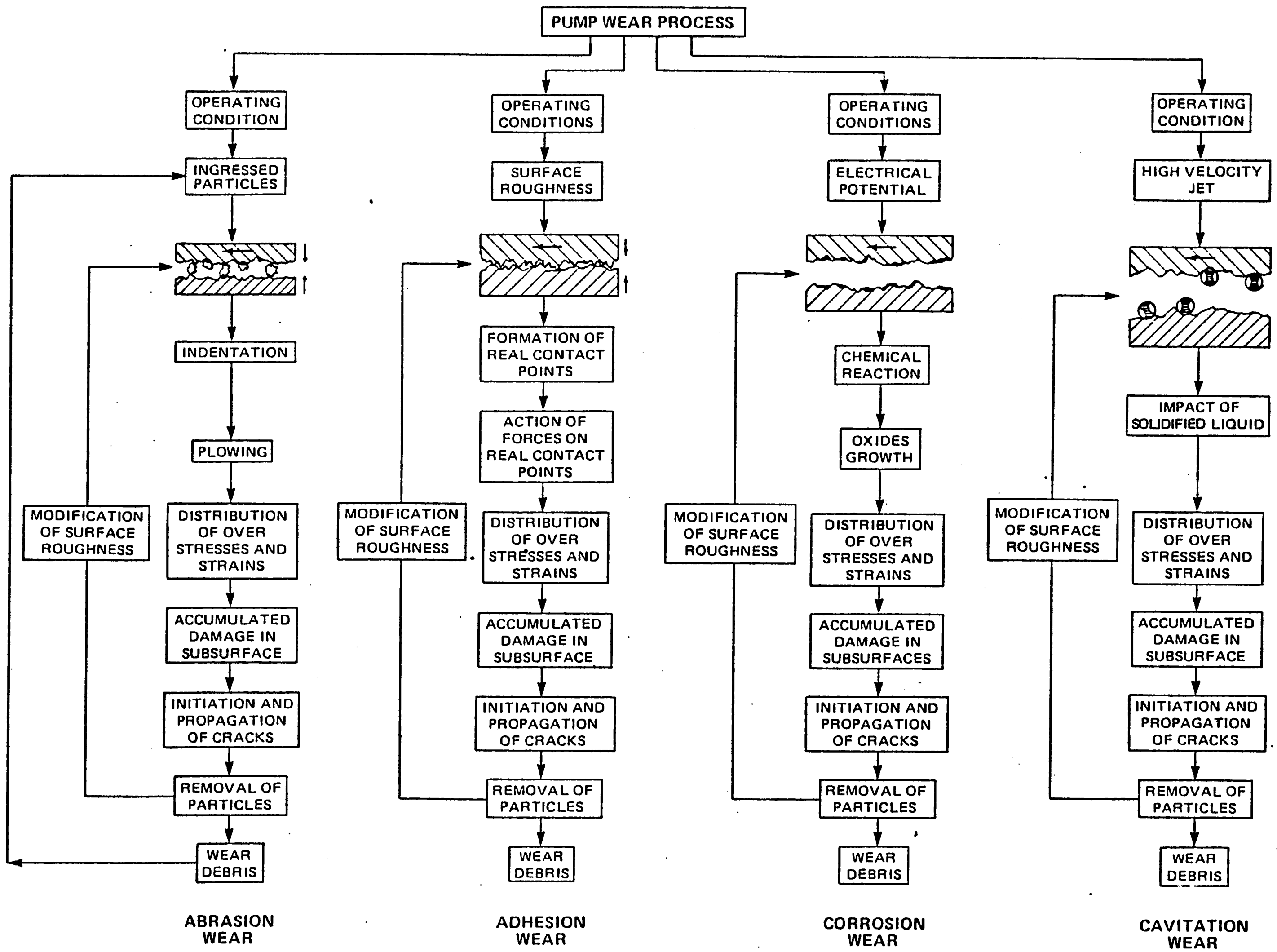


Figure 9. Breakdown of pump wear process

Pump Operation and Wear

A pump's performance depends on its operating conditions. Optimum pump performance is usually specified at conditions of minimum energy consumption. The basic pump performance parameters are flow, speed, torque pressure, fluid viscosity, and inlet pressure. For a given pump, in order to minimize friction, the combination of pressure, speed, and viscosity should be optimum (Figure 1). In order to maximize output flow, the combination of speed, pressure, and viscosity should minimize pump leakage flow. Pump volumetric efficiency provides a measure of the effect of internal leakage on the overall output flow. Furthermore, the pump design and operation must satisfy two demanding conditions: first, provide optimum hydrodynamic lubrication which produces minimal wear in all pump clearances, and second, minimize leakage flow. These two conditions mark the success of a given pump design. However, satisfying these conditions is not an easy task.

Figure 10 shows the initial clearances in an axial piston pump. Although piston clearances are nominally fixed, actual clearances vary with eccentricity due to load and viscosity. So, as is expected, the lubrication regime changes to boundary lubrication with the subsequent increase in friction and wear. Silva [51] experimentally showed the effect of pump clearances on overall pump efficiency at constant inlet pressure (Figure 11). The overall efficiency is the product of mechanical and volumetric efficiency. Lower

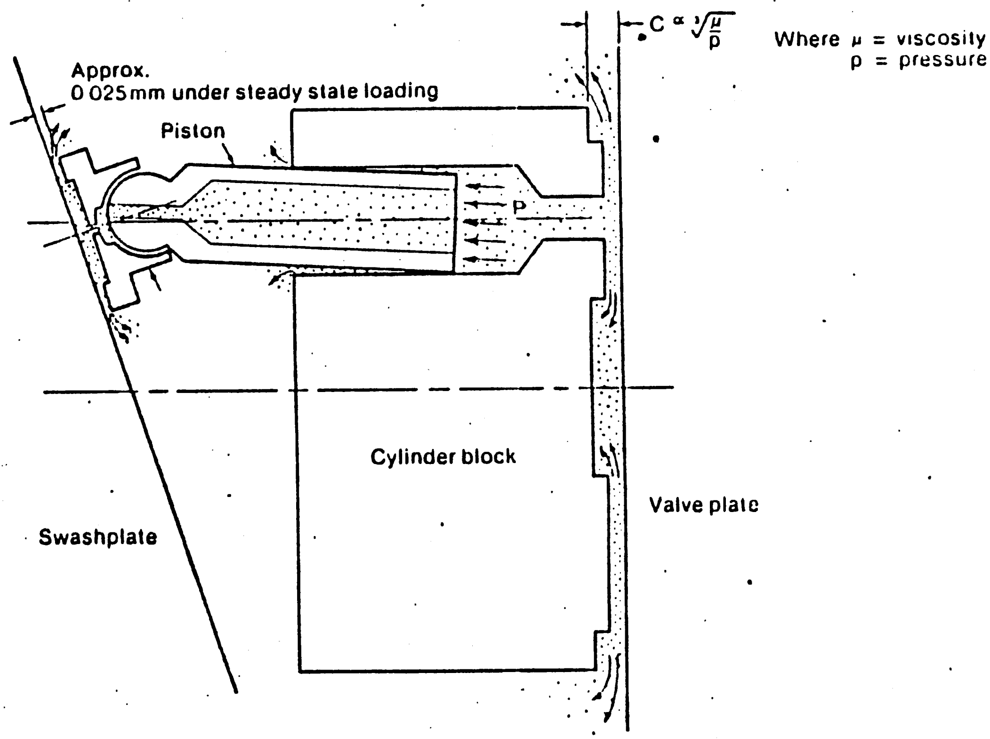


Figure 10. Piston pump clearances

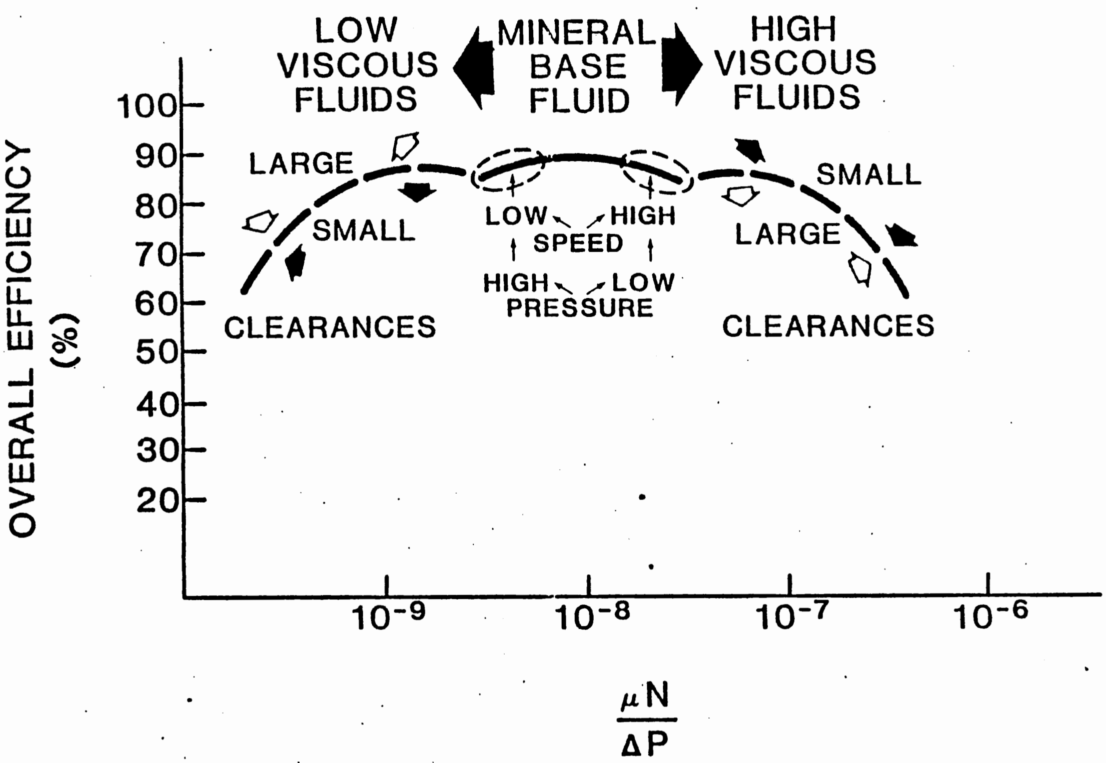


Figure 11. Effects of pump clearances on pump overall efficiency

overall efficiencies are observed on the extremes of the curve for mineral base fluid in Figure 11. At low speed and high pressure, the volumetric efficiency is lower and the mechanical efficiency is higher (low friction). At high speed and low pressure, the volumetric efficiency is higher and the mechanical efficiency lower (high friction) [48]. High mechanical friction is a characteristic of boundary lubrication. Boundary lubrication generates adhesion wear.

In addition, the effect of inlet pressure on pump operation is shown in Figure 12. The inlet pressure in Figure 12 is measured at the inlet port of the pump. Pressures at the pump suction chambers are lower due to pressure losses between the inlet ports and suction chambers. When the inlet pressure is low, pressure close to the vapor pressure of fluid cavitation occurs in the suction chamber. The presence of bubbles reduces pump output flow as shown in Figure 12. The trend in flow reduction indicates that when inlet pressure approaches -5 psi (10" Hg), a sufficient amount of cavitation is generated in the suction side to cause the output flow to drop below 80%. This cavitation effect generates bubbles that upon collapse generate a high velocity impact jet capable of breaking down any material.

Pump wear modes can be identified through their operating conditions. Therefore, different wear modes can be induced and analyzed independently or in combination by combining different pump operation conditions.

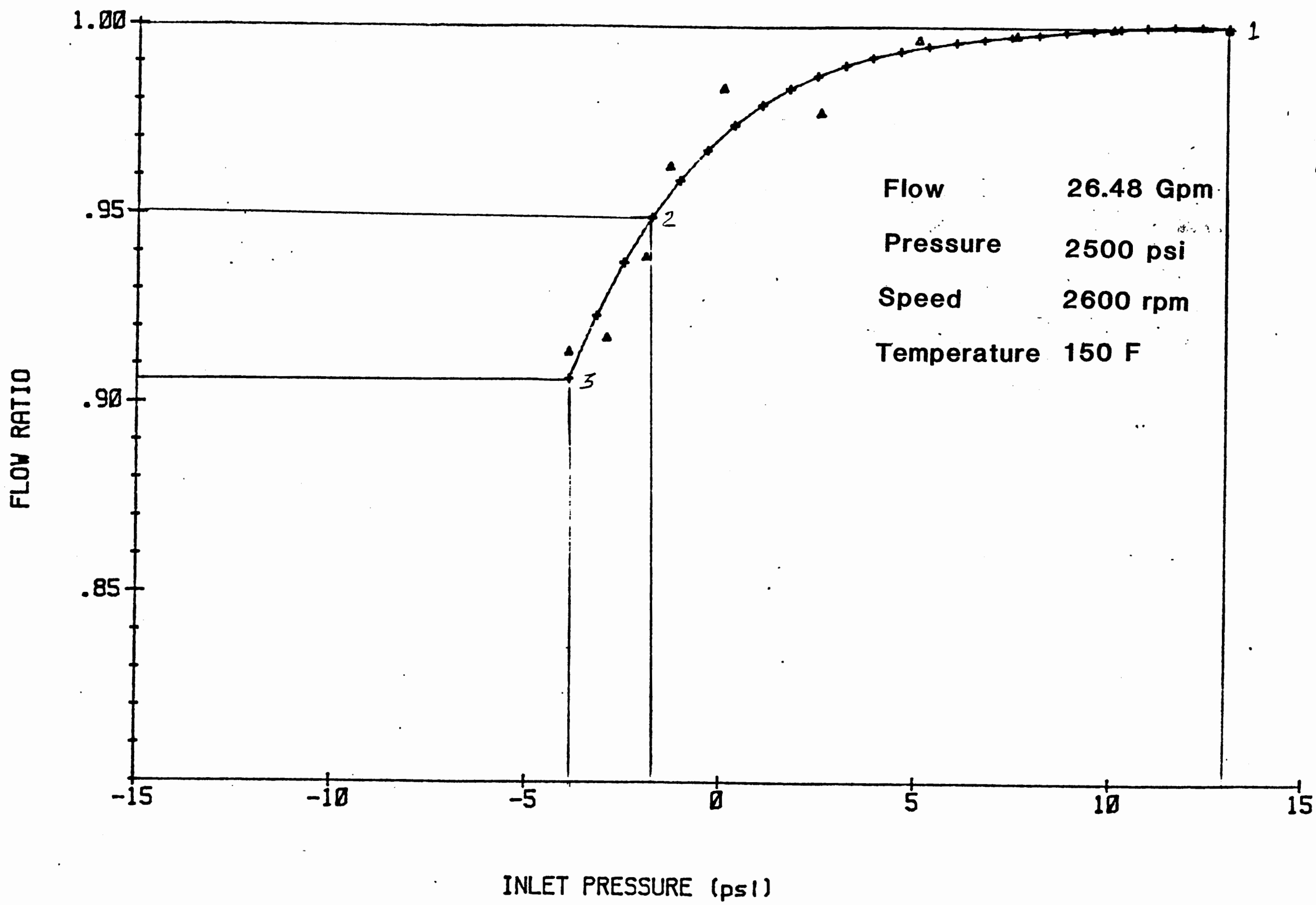


Figure 12. Pump filling characteristic

Synergistic Pump Wear

Synergism refers to cooperative effects -- effects that cannot be produced by the parts or individuals alone, or by any statistical summation of individual action [52]. Synergism refers specifically to combinatorial effects. The functional consequences of a synergistic phenomenon are always context-specific. They are determined by the properties of the phenomenon in question and by the system whose functional requirements may be served. The functional significance of synergism is always relational. In this research, the functional consequence of synergistic wear modes will be viewed in relation to total pump wear.

When comparing the stressing objects or trigger mechanisms of the four wear modes (assuming external ingression in abrasive wear modes), each can occur independently of the others. However, when external particle ingression does not occur, only three of the wear modes can be triggered independently: cavitation, corrosion, and adhesion. Abrasion requires the presence of wear particles of a size equal to the pump clearances. These particles can only be provided by either one of the other three wear modes or by the combination of all three. Thus, the abrasion wear mode is the synergistic effect of the other wear modes present in the pump.

Other synergism can occur when two or more wear modes trigger independently, producing more or less wear than the summation of the wear produced by each other. Unfortunately, in a hydraulic pump this type of synergism can only be examined through its effects on abrasive wear. The synergistic view of the above-mentioned pump wear process is proposed in Figure 13.

For a given pump operating under hydrodynamic conditions and without external particle ingression, several wear processes occur. The pump operates under a cavitation regime of high speed and low inlet pressure. When cavitation wear occurs in the inlet side, wear particles are produced. They become abrasive (three-body) in any or all of the pump clearances thus producing abrasion wear.

In addition, the pump operates with a fluid reach in oxygen through water in the system. This oxygen triggers a chemical reaction to form an oxide film. The removal of the oxide film is completed by either abrasion or adhesion. Corrosion wear particles produced by the mechanical factors become abrasive particles and generate abrasion wear.

The pump operates under low mechanical efficiency while the lubrication regime is on boundary condition. Adhesion wear particles are then produced that become abrasive particles in other pump clearances. Thus, considering that a pump is an enclosed compartment with clearances that change due to design and operating conditions, it is realistic to assume that particles generated internally cause abrasive wear.

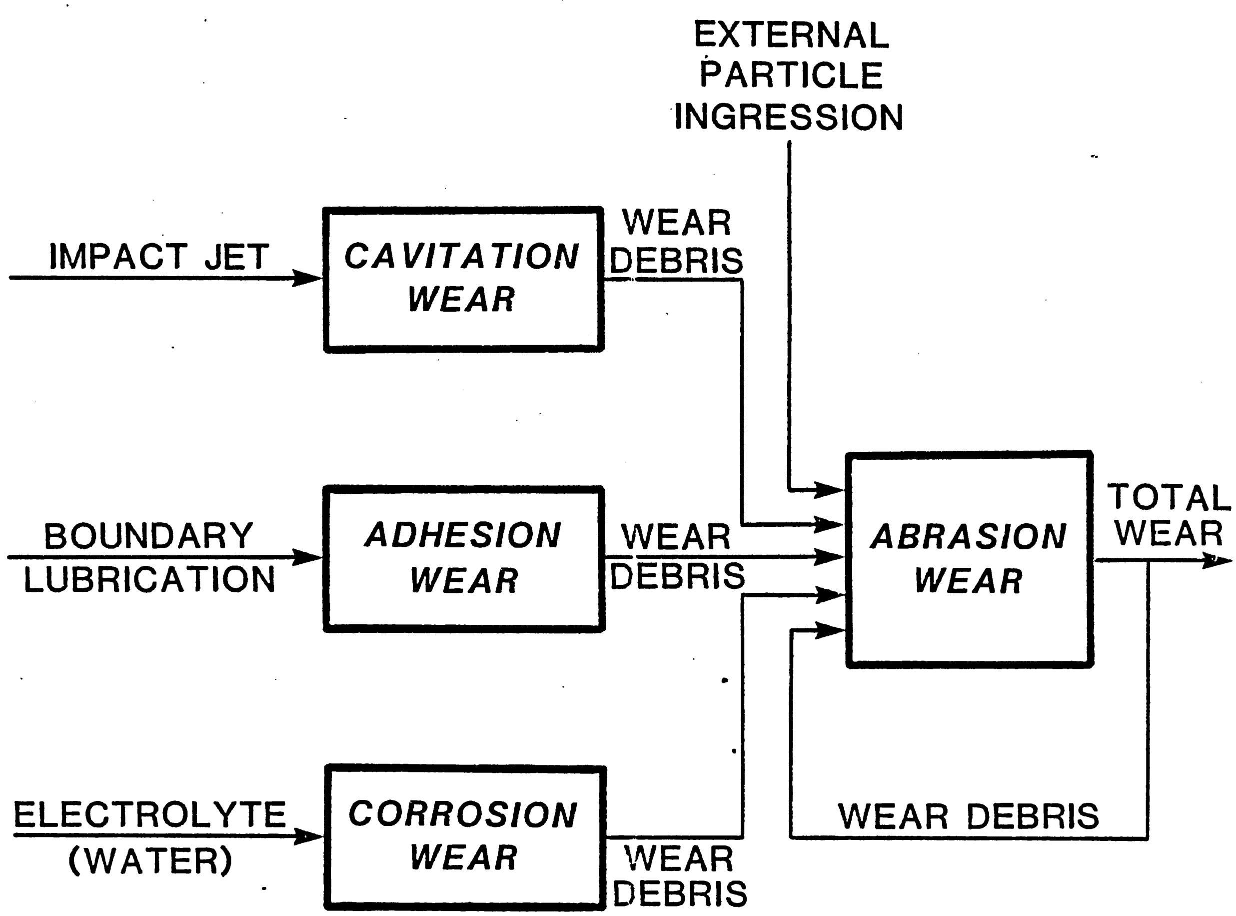


Figure 13. Synergistic view of pump wear process

CHAPTER IV

DEVELOPMENT OF THEORETICAL MODELS

In order to formulate an analytical expression to describe the synergistic process proposed in Figure 12, several steps must be followed. First, cavitation, corrosion, and adhesion models are required to estimate the mass of wear particles generated. These models were first derived generically and then were related to pump design and operating parameters. Second, an estimation of the damage caused by these particles is made through an abrasion model. Finally, the total amount of particle regeneration is estimated by adding the two above-mentioned models. A model for the total amount of wear obtained under combination of two or more wear modes is also proposed in conjunction with abrasive wear.

Cavitation Model

Most of the approaches employed to establish cavitation wear have been purely empirical [53]. However, using the universal law of wear (Eq. 1), the wear volume produced by cavitation wear can be theoretically estimated.

For a given material and constant conditions of speed, the amount of material removed by cavitation wear is proportional to the load , P, imposed upon the surface. In this case, load is generated by the impact jet created when bubbles collapse on the surface of a material. The impact forces created by the cumulative jets are described in Eq. (2) [30] and shown in Figure 4.

$$F = \frac{M\, v_1}{K_2(\tau_1 + \tau_2)} \qquad (2)$$

where F = impact force of cumulative jet

M = mass of fluid of the jet

v_1 = velocity of cumulative jet

K_2 = constant

τ_1 = relaxation time due to viscosity

τ_2 = relaxation time due to shear

According to the Kozyrev theory, the velocity of cumulative cavitation jet force is 2 to 8 times the bubble contraction velocity (Eq. (3)).

$$v_1 = K_1\, v_2 \qquad (3)$$

where K_1= 2-8

v_2 = bubble contraction velocity

The bubble contraction velocity can be estimated by Eq. (4) [40].

$$v_2 = \sqrt{\frac{2\, P_c}{3\, \rho}\left[\frac{R_o}{R_m}\right]^3 - 1} \qquad (4)$$

where Po = atmospheric pressure

p = fluid density

Ro = maximum bubble radius

Rm = minimum bubble radius

It can be seen from Eq. 4 that when R_m tends to zero, the velocity v_2 approaches an infinite value. Also from Eq. 4 the velocity of bubbles collapsing can be increased by increasing the pressure of the collapsing region.

The minimum and maximum bubble radii are determined by the following expressions (Eq. (5, 6)) [40, 41]

$$R_m = \frac{4\,\sigma}{3\,(P_o - P_v)} \tag{5}$$

$$R_o = \sqrt{\frac{1}{3}(\varepsilon - k)}\ \sqrt[3]{\frac{\varepsilon L_1}{k\ 1+\varepsilon}} \tag{6}$$

with

$$k = \frac{P_o - P_v}{\frac{\rho\, v^2}{2}}$$

where σ = liquid surface tension

v = fluid velocity

P_v = fluid vapor pressure

ε = rarefraction coefficient

L_1 = length of rarefraction zone

From Eqs.(2 - 6) it can be seen that the velocity required to create the necessary impact force is a function of the bubble size and bubble contraction velocity. Bubble size is a function of how close the system pressure is to the vapor pressure of the fluid. Low inlet pressures generate pressures close to vapor in the pump suction chamber. Then Eq. (2) is expressed as a function of P_I by Eq. (7).

$$F = \frac{M\, f(P_I)}{K_2\ (\tau_1 + \tau_2)} \tag{7}$$

where P_l = Pump inlet pressure.

The relation between inlet pressure to bubble generation and bubble contraction is very complex and therefore it has to be obtained experimentally. However, observations of Eq. (4, 5, and 6) suggest that a function $f(P_l)$ is inversely proportional to the difference between P_I and P_V. The function given by Eq. 8 is assumed.

$$f(P_I)\ \alpha\ \frac{1}{(P_I - P_V)} \tag{8}$$

where the exponent m has to be experimentally obtained.

Thus in the wear Eq. 1, the load L is equal to F of Eq. 7 for a constant condition of sliding distance and material hardness. The volume of wear is

$$V = \frac{K_3}{(P_I - P_V)^m} \qquad (9)$$

where K_3 is

$$K_3 = \frac{M}{K_2(\tau_1 + \tau_2)} \qquad (10)$$

In laboratory experiments, for a constant pressure, cavitation wear rate was found to follow the form of Eq. (11) [53, 54].

$$V = K_6 \ (1 - e^{-K_7 t}) \qquad (11)$$

where K_6 and K_7 are empirical constants.

Then with Eqs. (9 - 11), the wear volume produced by cavitation is given by Eq. (12)

$$V = \frac{K_8(1-e^{-K_7 t})}{(P_I - P_V)^m} \qquad (12)$$

where $K_8 = K_3 \times K_6$

or in mass units of cavitation wear removed

$$M = \frac{\rho K_8(1-e^{-K_7 t})}{(P_I - P_V)^m} \qquad (13)$$

Eq. (13) exposes the mass of wear produced by a given inlet pressure during a certain amount of time. This mass defines the amount of wear that will become abrasive in the system.

Corrosion Model

Corrosion wear is basically determined by the rate of formation of oxides and their removal. Batchelor [47] describes the formation of the oxide as

$$\delta^2 = tA_o e^{-E/RT} \tag{14}$$

where δ = oxide film thickness

t = time

A_o = Arrhenius constant

E = activation energy

R = universal constant

T = absolute temperature of the sliding surface

When t is equal to t_c, then δ is equal to δ_c, which is the actual oxide film thickness before its removal. Then, the volume of oxide to be removed is given by

$$v = \delta_c A \tag{15}$$

where A is the area of an oxide.

The time required to remove an oxide of length s at velocity v is equal to

$$t_c = \frac{s}{v\,K} \tag{16}$$

Corrosive wear can be calculated using Eq. (1) expressed as Eq. (17)

$$K = \frac{V\,H}{L\,X} \tag{17}$$

Thus with Eqs. (14), (15), (16),and (17) the volume of corrosive wear removed is obtained as shown in Eq. 18.

$$V = \frac{tA_o e^{-E/RT}\,L\,X}{H\,\delta_c^2} \tag{18}$$

By comparing Eq. (18) with Eq. (1), the term K is obtained as

$$K = \frac{tA_o e^{-E/RT}}{\delta_c^2} \tag{19}$$

This term K, in Eq. (19) represents the wear rate of corrosion wear and it is dependent on the oxidation rate. As was mentioned in previous chapters, the oxidation rate in lubricating systems depends on the amount of oxygen present in the lubricant. One way to increase the presence of oxygen in hydraulic systems is to increase the concentration of water in the system.

Experiments conducted by Xuan [55] and le Norman [56] suggest a linear relationship between the wear volume and the water concentration in the fluid. Thus

$$\frac{A_o e^{-E/RT}}{\delta_c^2} = A(PPM) + B \qquad (20)$$

where A,B = empirical constants

PPM = % of water in the system

Then with Eq. (18), (19), and (20) we obtain Eq. (21)

$$V = t(A(PPM) + B)\frac{L\,X}{H} \qquad (21)$$

Expressing Eq. (21) in mass units, Eq. (22) is obtained

$$M = \rho t(A(PPM) + B)\frac{L\,X}{H} \qquad (22)$$

which represents the amount of particles generated by corrosion that become abrasive in the system.

Adhesion Model

Adhesion wear in lubricated environments refers to the wear produced by the transfer and heating of contact asperities in boundary lubrication [15]. In boundary lubrication two surfaces in contact are only separated by their surface roughness or asperities. Under load the asperities of the softer material will deform, and with movement those asperities will be removed plastically Figure 6 [6, 11, 13, 24].

It is well known that generally the rough surfaces become smooth in boundary lubrication [9, 10, 24, 56]. During the smoothing process forward and side plastic flow occur as shown in Figures 14 and 15 [24]. From these figures we observe that the apparent area of contact increases with a decrease in surface roughness. A reduction in friction is also noticed with the smoothing process of rough surfaces [15, 57]. The reduction of friction takes place due to a decrease in asperity contact between the surfaces. For a given constant load a number of asperities are deformed and removed with the sliding speed. Then the two surfaces are no longer in contact but are separated by lubricated film and very few asperities. Furthermore, the friction between the two surfaces is reduced.

Thus, in boundary the rate of volume removed per unit time must be proportional to the volume available at asperity junctions and must diminish with time (Eq. (23)).

$$\frac{dV}{dt} = -G\,V \qquad (23)$$

where V = volume

G = proportional constant function at speed and available asperities

The solution of Eq. (23) is given in Eq. (24) assuming the volume generated at t = 0 is V_o.

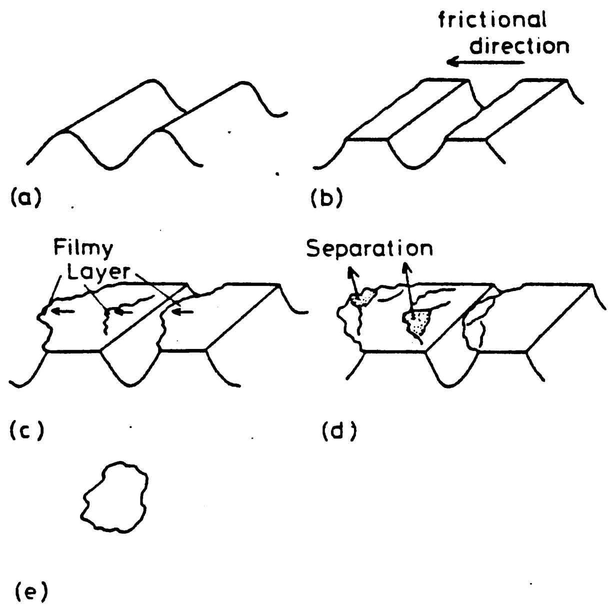


Figure 14. Wear particle generation under boundary lubricated conditions - forward plastic flow

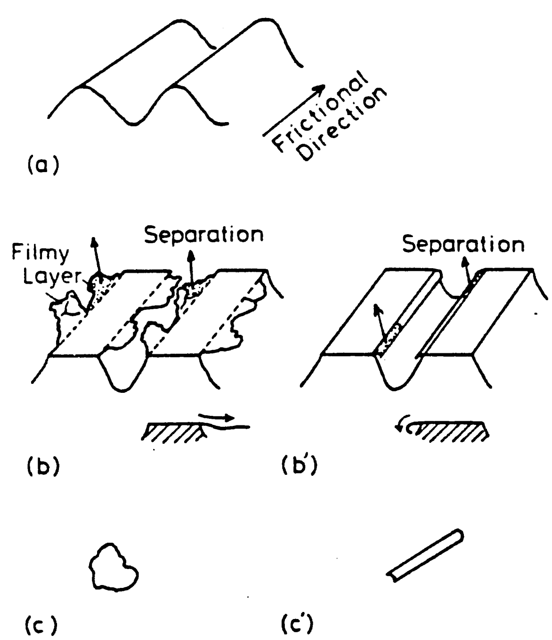


Figure 15. Wear particle generation under boundary lubricated conditions - side plastic flow

$$V = V_o e^{-Gt} \qquad (24)$$

The volume removed, V, at time t is equal to

$$V = V_o - V = V_o - V_o e^{-Gt} \qquad (25)$$

The initial volume Vo is generated by a load and can be approximated to be equal to the contact area A_t times the change in the center line of the surface roughness (Δ C_L) [58] expressed as follows.

$$V_o = A_t \ (\Delta C_L) \qquad (26)$$

Thus, combining Eqs. (25) and (26), Eq. (27) is obtained

$$V = A_t \ (\Delta C_L) \ (1-e^{-Gt}) \qquad (27)$$

The constant area A_t can be expressed as a function of load and field stress (or material hardness) as shown in Eq. (28).

$$V = \frac{L}{H} (\Delta C_L) \ (1-e^{-Gt}) \qquad (28)$$

In order to generate adhesive wear in pumps it is necessary to identify generating regions of high friction.

It was shown in previous chapters that high friction was recorded for pumps at low pressure and high speed. Friction is measured in pumps through pump mechanical efficiency. Thus, regions of high friction are identified by low mechanical efficiency. Typical pump efficiency test results are shown in Table I. The lowest mechanical efficiency is recorded at 500 psi and 2600 rpm.

When high friction occurs, the film thickness is reduced to allow asperity contact between two sliding surfaces. When analyzing pump design, this condition can occur only in the slipper, Figure 16. A slipper is a hydrostatic bearing designed to support load or fluid supplied from external sources. The hydrostatic bearings are also called thrust bearings. Shown in Figure 16 is a circular thrust bearing with a central pocket and a capillary tube. The pressure distribution in this bearing gives the load as a function of pocket pressure [59], Eq. (29).

$$W = \frac{\pi(P_r - P_o)}{8}\left[\frac{(D_2^2 - D_1^2)}{\ln \frac{D_2}{D_1}}\right] \tag{29}$$

The flow rate across the pocket through clearance h is given by Eq. (30).

$$Q = \frac{\pi h^3 (P_r - P_o)}{6\mu \ln(D_1/D_2)} \tag{30}$$

TABLE I

PUMP OVERALL EFFICIENCY

PRESSURE (PSI)	SPEED (RPM)	FLOW (GPM)	TORQUE (in-lb)	POWER IN (HP)	POWER OUT (HP)	VOLUMETRIC EFFICIENCY (%)	MECH. EFF. (%)
500	2600	27.0	257.	10.6	7.88	.984	.755
500	2200	22.9	249.	8.72	6.68	.985	.777
500	1800	18.7	251.	7.19	5.47	.987	.771
500	1400	14.6	248.	5.51	4.27	.989	.782
500	1000	10.5	229	3.63	3.06	.994	.848
1000	2600	26.8	463.	19.1	15.6	.978	.838
1000	2200	22.7	457.	15.9	13.2	.978	.848
1000	1800	18.6	459.	13.1	10.8	.979	.844
1000	1400	14.5	457.	10.1	8.46	.981	.848
1000	1000	10.3	449	7.12	6.06	.983	.865
1500	2600	26.7	669.	27.6	23.3	.972	.870
1500	2200	22.6	665.	23.2	19.7	.973	.875
1500	1800	18.5	667.	19.0	16.2	.974	.872
1500	1400	14.4	667.	14.8	12.6	.976	.873
1500	1000	10.3	669	10.6	9.05	.979	.871
2000	2600	26.6	875.	36.1	31.0	.970	.887
2000	2200	22.5	873.	30.4	26.3	.969	.889
2000	1800	18.4	875.	25.0	21.5	.969	.887
2000	1400	14.3	876.	19.4	16.7	.968	.886
2000	1000	10.2	889	14.1	11.9	.966	.874
2500	2600	26.4	1081	44.6	38.5	.963	.898
2500	2200	22.3	1080	37.7	32.6	.962	.898
2500	1800	18.2	1083	30.9	26.6	.961	.896
2500	1400	14.1	1085	24.1	20.6	.959	.894
2500	1000	10.0	1109	17.5	14.7	.955	.875
3000	2600	26.2	1287	53.1	45.9	.955	.905
3000	2200	22.1	1288	44.9	38.7	.953	.904
3000	1800	18.0	1291	36.8	31.5	.949	.702
3000	1400	13.9	1294	28.7	24.4	.942	.900
3000	1000	9.83	1329	21.0	17.2	.931	.877

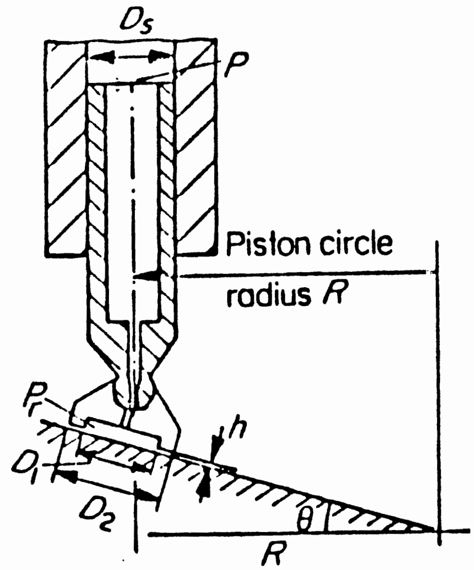


Figure 16. Simplified geometry of slipper path

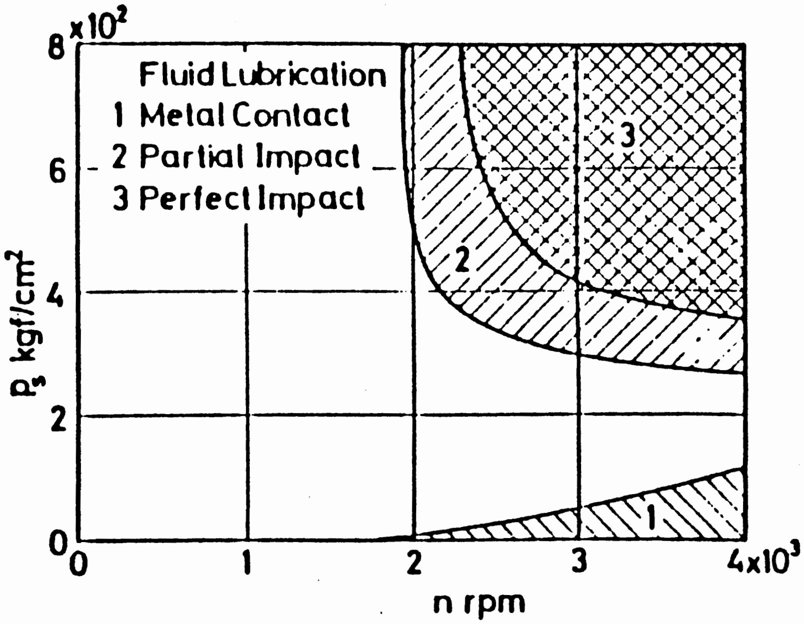


Figure 17. Limit of fluid film lubrication for slipper bearing [59]

This flow in Eq. (30) is the same flow passing through the capillary tube. The flow through the capillary tube is given by Eq. (31).

$$Q_c = \frac{\pi d_c^4 (P_r - P_o)}{128 \mu L_c} \tag{31}$$

where dc = diameter of capillary tube

lc = length of capillary tube

μ = viscosity

P = pressure

The load capacity can be derived using Eq. (29), (30) and (31).

$$W = \frac{\pi(D_2^2 - D_1^2) P}{8 \left(\frac{64 L_c h^3}{3 d_c^4} + \ln(D_2/D_1)\right)} \tag{32}$$

From Eq. (32), it can be deduced that for a constant load to maintain the same clearances, pressure P should increase. Otherwise, h will be reduced. The effect of reduced pressure increases the friction between pump slippers and swash-plate. This fact has been studied by other authors from the point of view of performance but not wear (Figure 17) [60].

In order to provide a good separation between the clearance, h should be larger than the surface roughness C_L. The degree of surface separation in a lubricated contact can be defined as the ratio of the lubricant film thickness to the composite roughness.

$$\lambda = \frac{h}{C_L} \tag{33}$$

Then in Eq. (28), the term ΔC_L can be expressed as a function of λ which relates generic adhesive wear to adhesive wear in pumps. Thus

$$V = \frac{L}{H} \lambda \ (1-e^{-Gt}) \tag{34}$$

The variation of λ is related to the variation of friction (mechanical efficiency) vs. pressure found in Table I. The term λ is one indication of friction. The term λ is a function of pressure P (Eqs. 32, 33). Figure 18 shows the variation of the mechanical efficiency as a function of P. At low pressure, λ increases. Thus, when the pressure increases, the friction in the slipper reduces and high mechanical efficiency is obtained.

Using Table I, Eq. (34) can be expressed as

$$V = \frac{L}{H} \frac{(k)}{P} \ (1-e^{-Gt}) \tag{35}$$

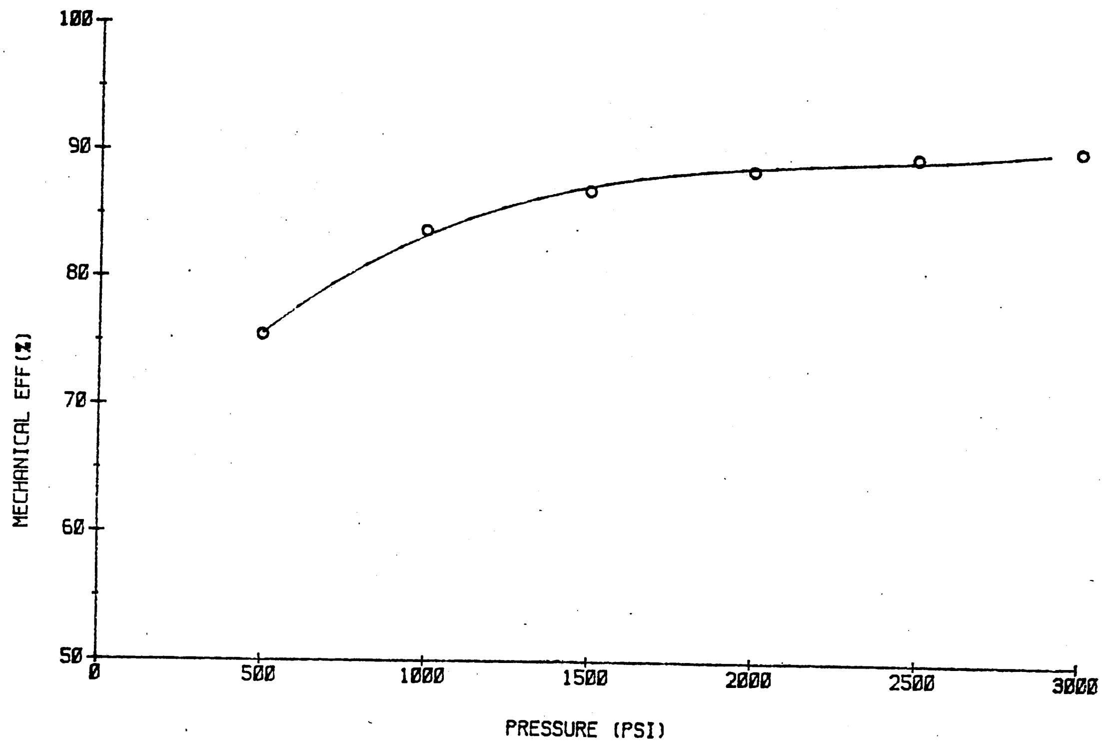


Figure 18. Variation of pump mechanical efficiency as function of system pressure.

For P $\leq$ 2000 psi or as

$$V = \frac{L}{H} (1.0) \; (1-e^{-Gt}) \tag{36}$$

For P $\leq$ 2000 psi

For a constant load and material hardness in boundary lubrication, the constant G is a function of velocity and material roughness.

Abrasion Model

Studies on three-body abrasive wear of lubricated contacts have mainly concentrated on the role played by particulate parameters. These are hardness, size roughness, concentration and shape [17, 18, 61, 62]. These factors are very important because in industrial applications particulate induced wear cannot be totally controlled. A filtration system prevents the passage of particles higher than specific film thickness. However, as will be shown later, in most of the cases the dimension of the internal clearances for a given pump varies considerably. Filters that prevent the passing of very small particles (1 -2 microns) are not usually used in industrial applications. Thus, abrasive wear is very likely to be found in any lubricated-type of equipment.

In order to establish the total amount of wear removed during abrasion, the amount of wear removed per particle should be defined. In general, the amount removed in abrasion wear is a function of the particles and as in any other wear mode a function of the load, speed, and material hardness (Eq. (1)). When the latter parameters are maintained constant, abrasive wear can be expressed by Eq. (37).

$$V = F(d_i ,h , H_p ,Q ,t ,C_i) \tag{37}$$

where di = particle size i

h = film thickness or clearances

Hp = hardness of particle

Q = flow rate through clearances

t = time

Ci = concentration of particles of size i

Other parameters such as roughness and shape are not considered here and are still a matter of current research [62].

Several assumptions are made at this point:

1. Particles of extremely large size cannot pass through clearances.
2. The particles must be of a dimension slightly larger than the film thickness to cause abrasive wear.
3. After the particles have been through the clearances, the clearances increase in size.
4. When the abrasive wear process is established, most of the particles of size equal to or

smaller than the maximum available clearances are present in the system.

Thus, the variation of abrasive wear removed per unit of time under a given concentration of particles depends on the volume available to be removed at clearances by particles of dimension higher than clearances and must diminish with time

$$\frac{dV}{dt} = -V_a C \tag{38}$$

where Va = abrasive volume

C = proportional constant function of particle concentration, shape, abrasity toughness

The solution of Eq. (38) is given in Eq. (39)

$$V_a = V_{ai} e^{-Ct} \tag{39}$$

Assuming volume available at time = 0 is V_{ai}, the abrasive volume removed at time t is equal to

$$V_a = V_{ai}(1-e^{-Ct}) \tag{40}$$

The total volume V_{ai} can be expressed as Eq. (41)

$$V_{ai} = \alpha N_p \tag{41}$$

where α = volume generated per particle

N_p = total number of particles capable of causing damage.

The total number of particles N_p is dependent on the wear generation mechanism or wear mode. Then

$$N_p \propto V_w \quad (42)$$

where V_w = volume of wear produced by the present wear mode

There

$$V_a = \alpha \, (kV_w) \, (1-e^{-Ct}) \quad (43)$$

Expressing α times K as K

Then

$$V_a = (kV_w) \, (1-e^{-Ct}) \quad (44)$$

Equation (44) expresses the abrasive wear volume generated as a function of time.

The exponential decay wear given by equation (44) has been found empirically by other researchers [64, 65]. Often abrasive wear is expressed as a function of clearance variation [18, 49]. In pumps, for instance, clearance increase means more leakage flow. Leakage flow reduces pump output flow. Then pump output flow varies inversely with pump wear. Figure 19 shows the variation of pump flow found under particle-induced wear experiments.

Combinatorial Model

The particles passing through the pump clearances are a function of the generating mechanism or wear mode (Eq. (44)). Wear modes generate particles, and, depending upon their size, these particles generate abrasive wear. The total wear volume can be expressed by Eq. (45).

$$V_t = V_w + V_a \tag{45}$$

where V_T = total wear volume

V_W = wear mode volume

V_a = abrasive wear volume

Using previously derived equations for different wear modes, the total wear volume generated can be calculated. For cavitation the total wear is derived using Eq. (12, 44 and 45) expressed as Eq. (46).

$$V_t = V_w + (kV_w)\ (1-e^{-Ct}) \tag{46}$$

Using Eq. (12, and 46), Eq. (47) is obtained.

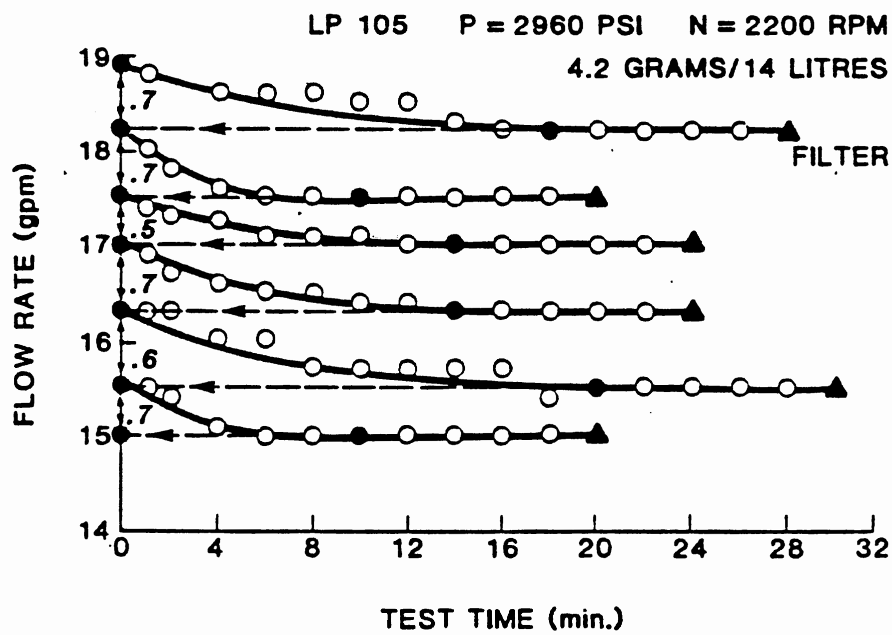


Figure 19. Pump flow degradation from multiple injections

$$V_t = \frac{K_8(1-e^{-k_7 t})}{(P_I-P_v)^m} + \frac{k(K_8(1-e^{-k_7 t}))}{(P_I-P_v)^m}(1-e^{-Ct}) \tag{47}$$

However, cavitation wear is a faster phenomenon than abrasive wear. Cavitation bubbles develop at a high frequency ranging from 5×10^2 to 10^3 bubbles per second [39]. Abrasive wear is dependent on the flow through clearances and the concentration of particles. Thus, while cavitation wear has produced particles, it takes longer for these particles to cause damage. Therefore in Eq. (12) the time of cavitation to steady-state is small in comparison with the time for abrasive wear. Furthermore, Eq. (47) can be simplified as

$$V_t = \frac{A}{(P_I-P_v)^m} + \frac{B\ (1-e^{-Ct})}{(P_I-P_v)^m} \tag{48}$$

where A and B represent constants

$$A = K_8(1-e^{-k_7 t})$$

$$B = k\ A$$

Eq. (49) expresses the volume produced by cavitation in conjunction with abrasion wear as a function of pump inlet pressure. For a constant inlet pressure, the total volume is expected to increase exponentially and reach a steady-state value depending on time constant C. At constant time, the total wear in Eq. (50) is an inverse function of the inlet pressure. The coefficients m, A, B, C, of Eq. (50) need to be experimentally obtained.

The following equations were obtained for adhesion and corrosion. Using the same rationale as above for cavitation, similar assumptions were made concerning the time employed by the wear modes to reach steady-state; it is very small compared to the time for the abrasion mode to reach steady-state.

For corrosion wear using Eq. (22, 44, and 45), the total volume synergistically generated by corrosion is given

$$V_t = \frac{1}{(P_I - P_v)^m}(A + B(1 - e^{-Ct})) \tag{49}$$

where

$$V_t = (PPM)\ (D + E(1 - e^{-C_o t})) \tag{50}$$

$$D = \rho t A\left(\frac{L\ X}{H}\right)$$

$$E = Bt\left(\frac{L\ X}{H}\right)$$

C_o = time constant

Then, for a constant time, Eq. (50) indicates that the total volume generated by corrosion wear is a linear function of the water accumulation in ppm. For a constant ppm. Eq. (50) also indicates that the total wear reaches steady-state depending on time constant C_o.

The total volume of wear synergistically generated by adhesion is obtained using Eq. (35, 44, 45) under the same assumptions previously mentioned.

$$V_t = \frac{1}{P}\left(k_1 + k_2\left(1-e^{-C_a t}\right)\right) \tag{51}$$

where $K_1 = \frac{L}{H} k\left(1-e^{-Gt_o}\right)$

$k_2 = k_1 k$

The combinatorial model that includes the effects of the three wear modes is given in Eq. (52) under the same assumptions stated before and assuming linear combinations of wear generation. Eq. (52) is given in a simplified form. It, in conjunction with Eqs. (11, 21, 35, 44, 45), gives

$$V_t = \left[\frac{A_1}{(P_I - P_v)^m} + B_1(PPM) + \frac{C_1}{P}\right]\left(D_1 + E_1\left(1-e^{-C_c t}\right)\right) \tag{52}$$

where A_1, B_1, C_1, D_1, E_1, and C_c are constants to be obtained empirically. Verification of the models presented in this chapter is done using the experimental results discussed in the next chapter.

CHAPTER V

EXPERIMENTAL RESULTS OF SYNERGISTIC PUMP WEAR

In this chapter the synergistic wear produced by cavitation, corrosion, and adhesion wear modes is investigated experimentally using actual pumps. The synergistic wear produced by each wear mode is evaluated independently and in combination with the other two modes. This chapter first discusses the experimental program and considerations formulated to satisfy the research objectives. Secondly, the test procedures and equipment utilized are discussed. Then, experimental results are presented and analyzed. Finally, correlation to previous theoretical analyses is made in the Model Verification section.

Experimental Program

When several factors are to be systematically studied, a factorial experiment first comes to mind. However, the number of experimental units and their cost are usually limiting factors in factorial experiments. For this research seven identical pumps were available. Taking into account that this research was the first of its kind, an experimental program was designed to obtain as much information as possible and to provide supporting data for future investigations of this kind.

Seven experiments using cavitation, corrosion, and adhesion plus their combinations were proposed. Each experiment was conducted at three different levels of severity. At each level of severity, wear concentration was measured. The level of severity of each wear mode was controlled by the independent stressing parameter defined in Chapter IV: inlet pressure for cavitation, boundary lubrication for adhesion, and water content for corrosion. The levels of severity for boundary lubrication were obtained by employing different pressure levels. Table II lists the proposed experiments. One pump per experiment was used. These experiments were factorially designed, but without replication. A base line defining normal levels for each wear mode was repeated for all seven experiments. Normal conditions existed when the pump did not experience any significant wear mode or when the mode's effects were minimal. Normal conditions are listed below.

Pressure:	2500 psi
Speed:	2600 rpm
Inlet Pressure:	13 psi
Temperature:	150^{o}F
Water Content:	400 ppm
System Fluid:	MIl-L-2104

Using data from a normal base line it was possible to detect possible differences between the normal wear of the pumps being tested. The type of tests conducted for each pump are summarized in Table III. The severity levels shown

TABLE II

PROPOSED EXPERIMENTS

Test No.	Experiment	Treatments
1	Cavitation	3
2	Corrosion	3
3	Adhesion	3
4	Cavitation Adhesion	5
5	Cavitation Corrosion	5
6	Corrosion Adhesion	5
7	Cavitation Corrosion Adhesion	5
		33

TABLE III

PROPOSED EXPERIMENTAL DESIGN

WEAR MODES										
ADHESION (PRESSURE PSI)		2500			500			200		
CAVITATON (INLET PRESSURE)		10 PSI	-4 inHg	-8 inHg	10 psi	-4 inHg	-8 inHg	10 psi	-4 inHg	-8 inHg
CORROSION (WATER CONTENT) (PPM)	500	1 2 3 4 5 6 7	1	1	3	5	5	3	5	5
	1000	2	4	4	6	7	7	6	7	7
	2000	2	4	4	6	7	7	6	7	7

in Table III correspond to those typically found in actual pump operating conditions.

Test Equipment and Procedures

The testing units used for this experiment were seven identical variable displacement pressure compensated axial piston pumps. The pumps were tested under fixed displacement conditions and under pressure condition below the compensator setting. Table IV summarizes information relating to pump specifications.

Each pump was installed in a test stand with controls capable of satisfying pump test conditions. Figure 20 shows the hydraulic test circuit. This system also allowed the by-passing of its filter during testing so wear debris could be built-up in the system. System volume in circulation was also adjustable and it was maintained at 9.5 liters.

In order to establish wear trends, monitoring of wear debris generated by the pump was required. There are several methods to establish the wear content in hydraulic fluids. They include ferrography, gravimetric analysis, particle counts, and others [66]. However, most of these methods are time consuming and require the fluid sample to be sent to a laboratory for analysis.

The selection of a method which allowed the detection of wear during the test was required in order to establish variation in the pump wear rate. Recently a new method has become available [67]. The wear analyzer uses a magnetic

TABLE IV

SPECIFICATIONS OF PUMPS

Specifications	Units	
Displacement	in^3/rev	2.44
Max Speed	rpm	2500
Rated Pressure	psi	3000
Min Pressure	psi	75
Min Inlet Pressure	psig	-3.0
Recommended Viscosity	ssu	80-

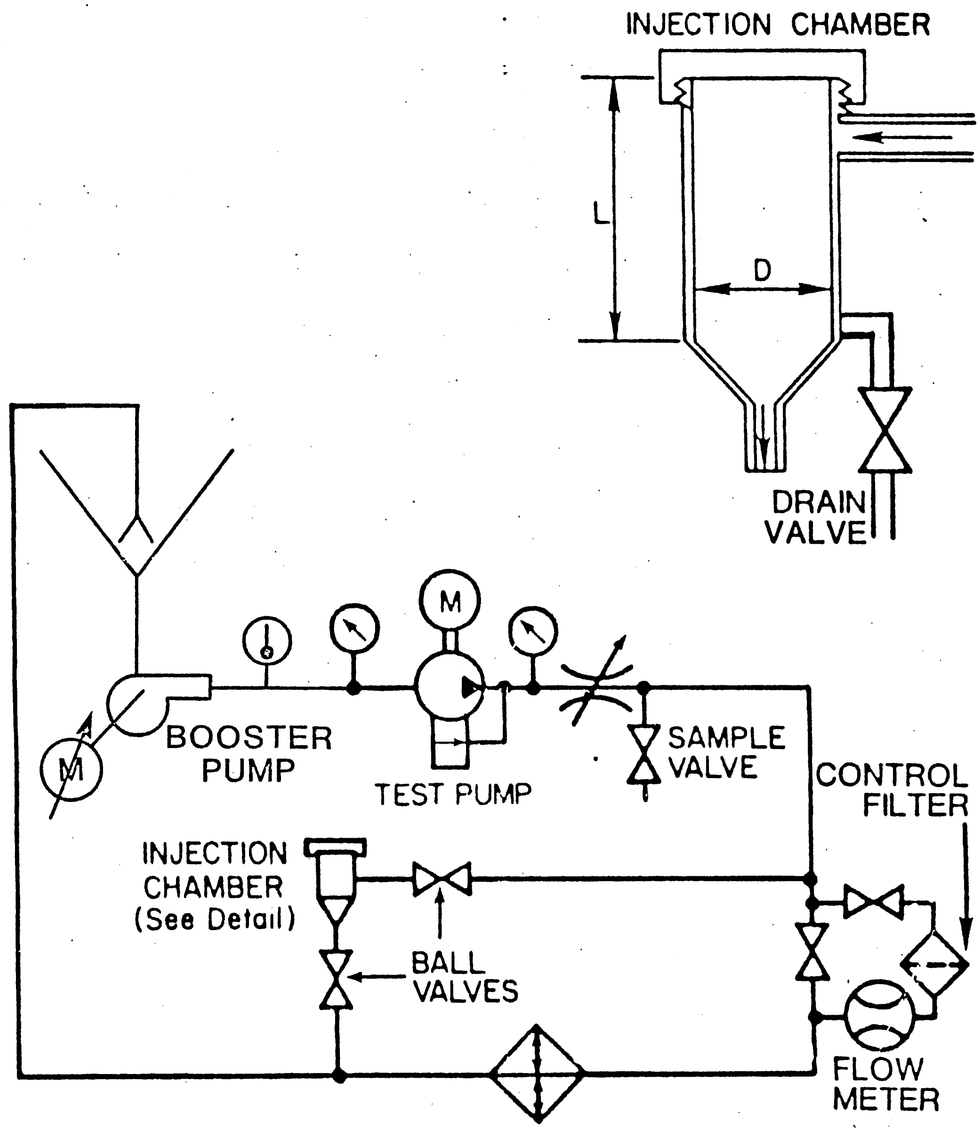


Figure 20. Test circuit

filter to capture particles and measures the concentration of particles in ppm/oz mass of fluid. PPM is defined as parts of metallic iron present in a million parts that constitutes one ounce mass of fluid taken as a sample [17]. This method was selected because of its potential to establish wear during tests. Concentration of wear in these tests was expected to be low, so testing of the wear analyzer was performed to establish the linearity in the readings and to detect the proper magnetic filter for capturing the particles. Figure 21 shows the linearity of the instrument to different calibrated fluid samples. One of the drawbacks of this instrument is that it only measures concentration of magnetic particles; therefore, other post-test analyses of fluid during sample tests were done using a particle counter and the gravimetric analysis method.

Each pump was subjected to a standard two-hour break-in procedure [68]. In this test, pressure was gradually increased on the pump up to rated pressure where the pump operated for one hour. After the break-in test was performed, the pump was ready for testing. The following test procedure was followed for each pump. Starting with clean fluid, system filters were by-passed and wear produced during normal conditions was established. This base line wear is a common test for oil pumps. The duration of this test was six hours. Wear build-up was measured every 30 minutes using the wear analyzer instrument. Samples of fluid were taken every four and six hours. The six-hour

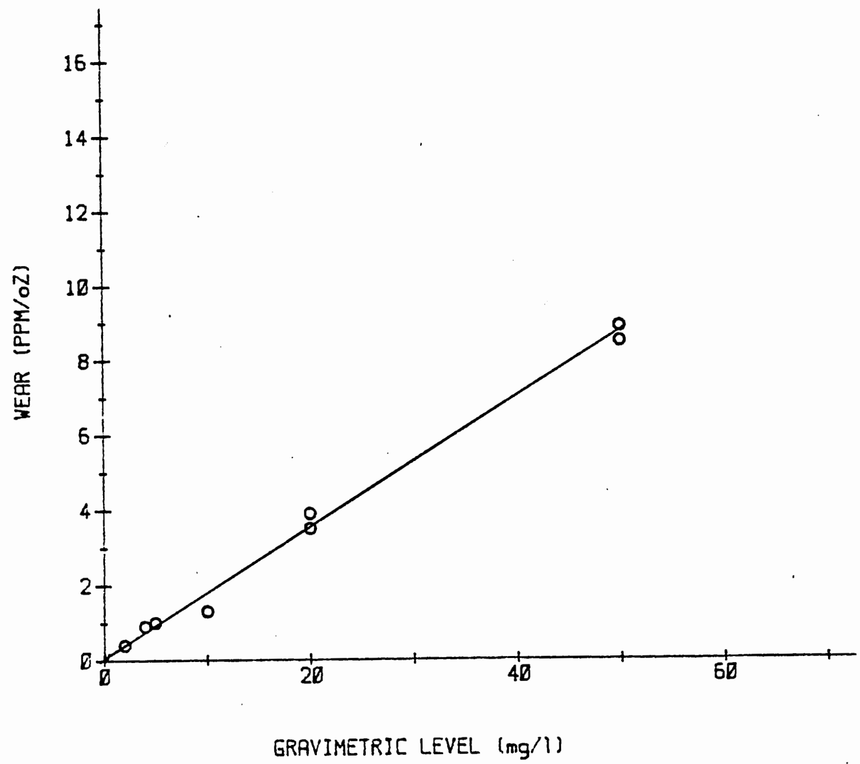


Figure 21. Sensitivity of wear analyzer readings

time span was selected observing that wear in previous experiments [63] reached steady state after 2-3 hours. The assumption of six hours proved to be sufficient to detect the steady state wear rate. Next, each test system fluid was filtered for 20 minutes. Then the system filter was by-passed and a desired wear mode was induced. Wear build-up was monitored using the wear analyzer every 30 minutes during the six hour period. After filtering for 20 minutes, filters were by-passed again. Next, the severity of the induced wear mode was increased and the same procedure was repeated. This test procedure is shown in the flow chart presented in Figure 22.

Experimental Results and Data Analysis

Cavitation Test

The above mentioned test procedure was first performed for cavitation. In order to induce cavitation wear, a filling characteristic pump test was first performed. Figure 12 presents the results of this test. At constant speed and temperature the effects of inlet pressure are shown as reduction of pump outflow. Three operating points were selected. They were the operating point at which the pump experienced flow degradation of 0% at normal, 5% at -4 in Hg, and 10% at -8 in Hg (Figure 12).

The effects of reduced inlet pressure on pump wear are shown in Figure 23. Under normal conditions the wear generated by a pump is very limited -- below 0-5 ppm. Wear

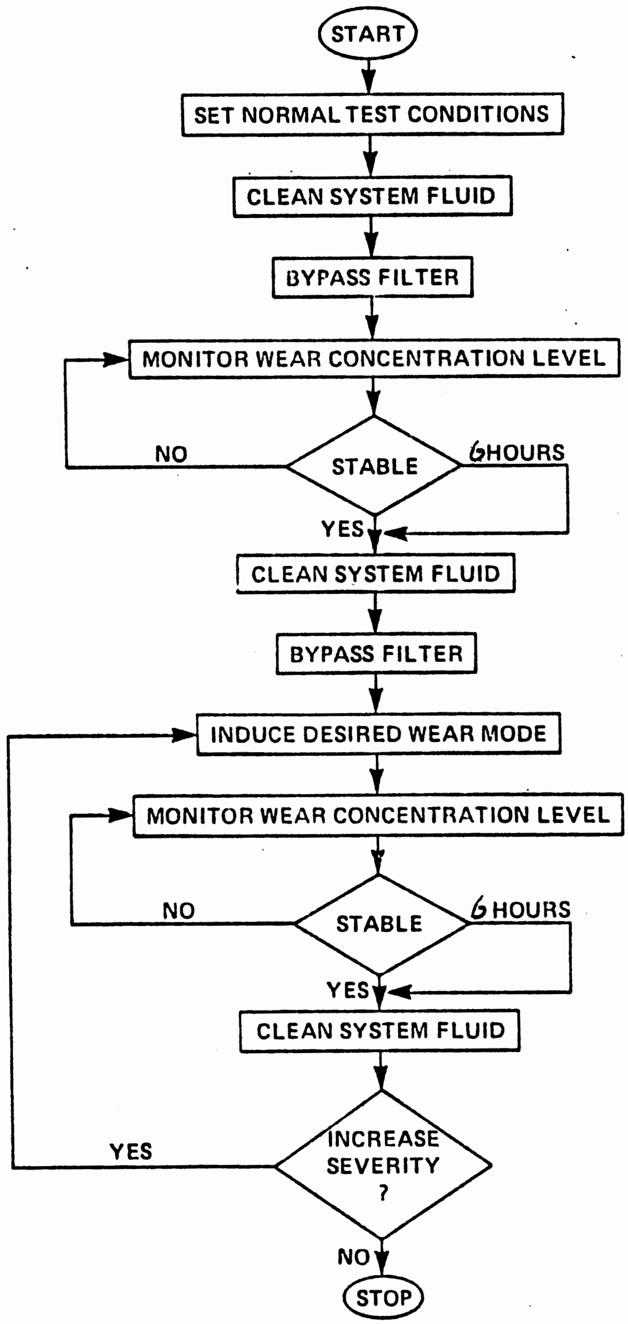


Figure 22. Experimental test procedure

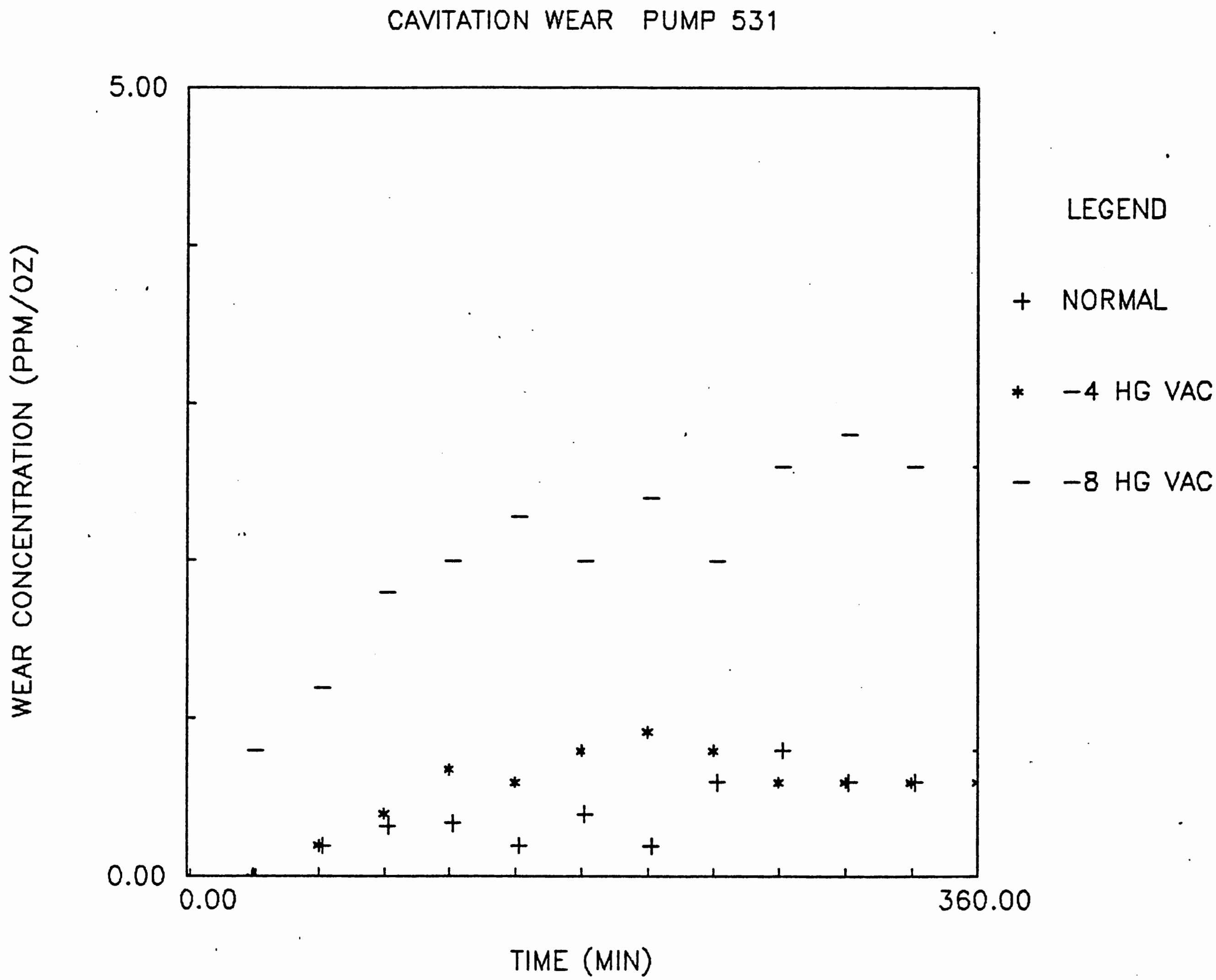


Figure 23. Magnetic wear debris generation under cavitation conditions

concentration reaches a steady state value after approximately four hours. This time is determined by the system volume and wear generation. It is the time the particles generated by a normal mechanism take to reach an equilibrium between generation and damage. With reduced inlet pressure (5% reduction in output flow) a slight increase in wear concentration is observed. This suggests that the bubbles generated by this low pressure are a few, yet large enough to provoke a strong high velocity jet capable of damaging the material and producing particles of dimension larger than pump clearances. The effects of severe cavitation are evident at -8 in Hg. The concentration increases approximately three times and the time to reach steady state is longer. This fact suggests that the cavitation generation and its abrasivity effects are active for longer periods due to the increased presence of particles larger than pump clearances.

Similar results were observed when particle size distribution was determined using a particle counter. Figure 24 compares the particle distribution of clean fluid or background particles, normal wear and the build-up of wear due to the abrasion effects of cavitation. The number of particles larger than 5, 10, 20, and 30 microns increases with the cavitation severity. The increased concentration of larger particles indicates the enlargement of pump clearances. Visual examination of cavitation damage suggests the presence of particles up to 80 to 100 microns

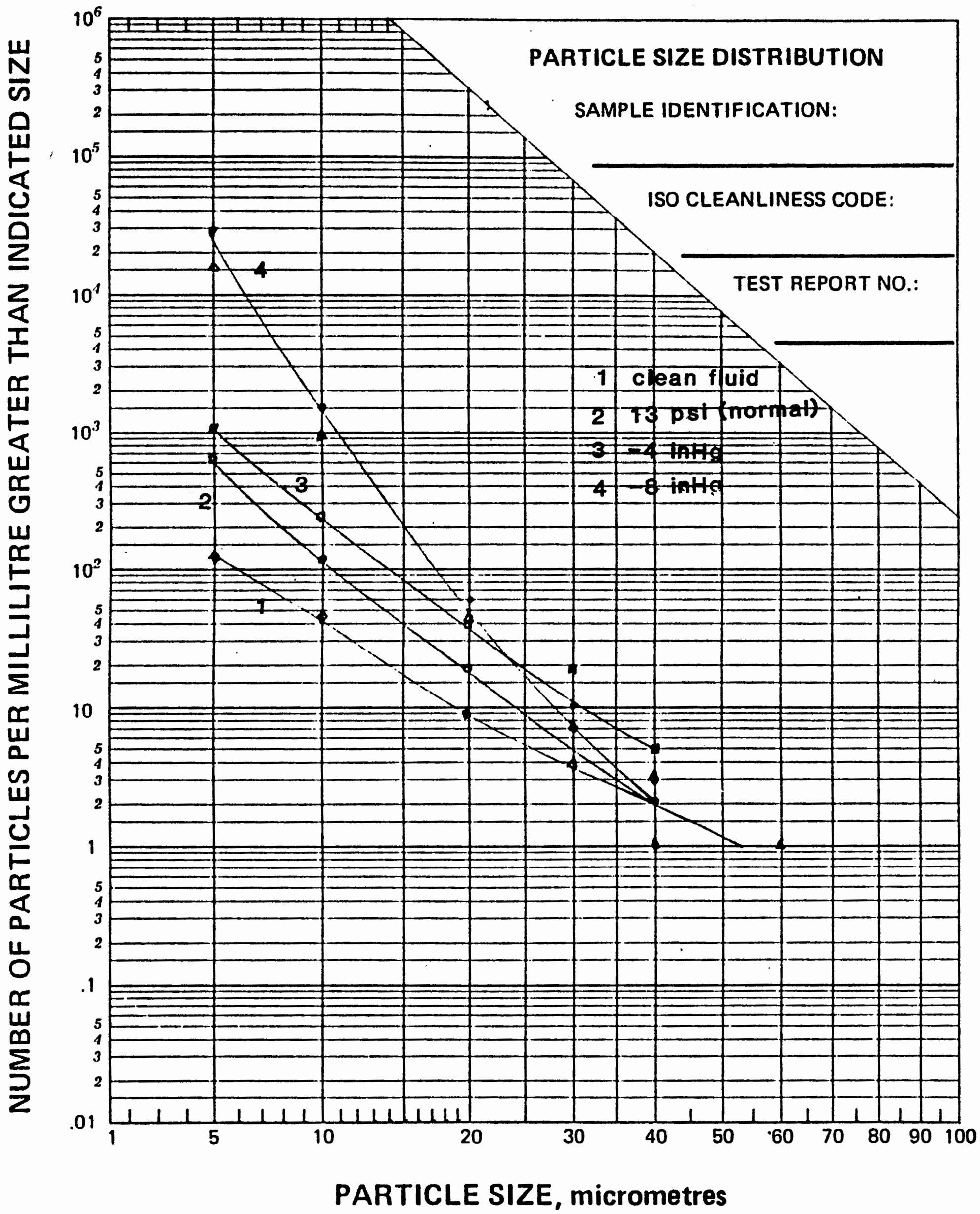


Figure 24. Particle size distribution obtained after six hours of testing. Cavitation wear - Pump 531

(Figures 25 and 27). However, particle analysis only shows particles smaller than 40 microns. The explanation given is that pump clearances act as filters, and if a large particle passes through, it will be reduced to the same size as an enlarged clearance. Data supporting this will be shown later.

Figure 27 shows the changes in the fluid gravimetric levels obtained after six hours of cavitation testing. Normal conditions show, as it should be, low fluid gravimetric levels (below 5 mg/l). With cavitation conditions set at 0.85 Atm (-4 in Hg), the fluid gravimetric level increases up to 17 mg/l due to the presence of cavitation wear. When cavitation conditions are more severe -- 0.75 Atm (-8 in Hg), the gravimetric level of the fluid increases drastically reaching a dangerous 68 mg/l.

Thus, similar results were obtained with three different methods of wear debris quantification -- wear analyzer, particle counts, and gravimetric levels. This fact suggests that either of these three methods can be used to measure wear debris produced by pump wear modes. However, the use of all three of these methods provides more complete information regarding the nature of wear that is magnetic or paramagnetic, the particle size and the total concentration of wear in the fluid. This information is very important in decisions regarding system diagnosis and system maintenance.

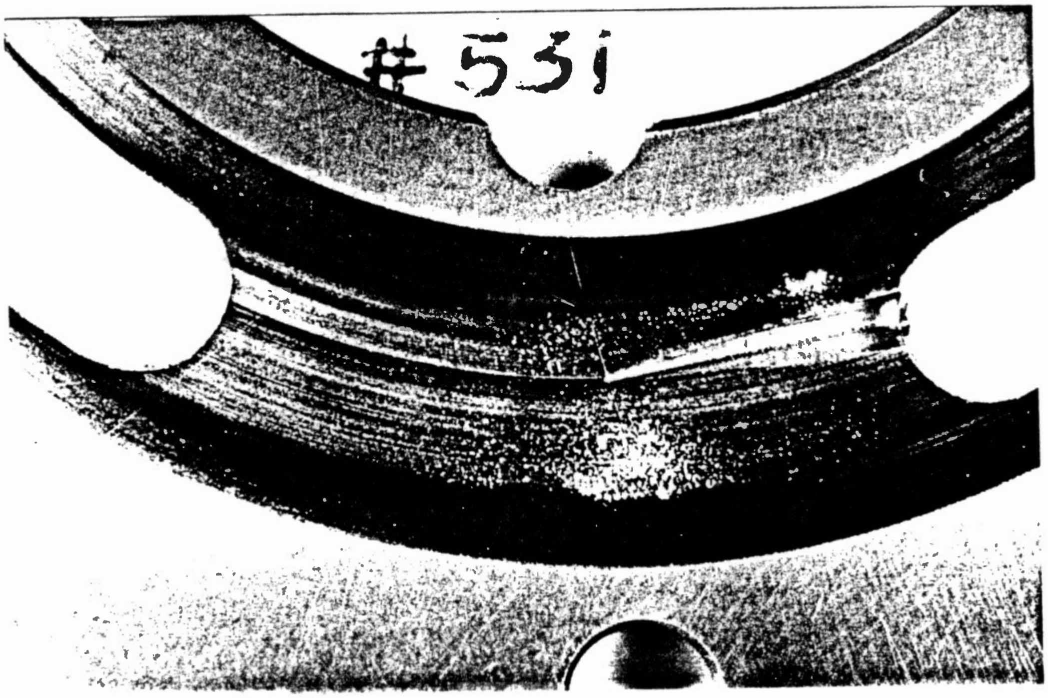


Figure 25. Cavitation wear damage on a port plate

Figure 26. Microscopic view of port plate cavitation wear damage

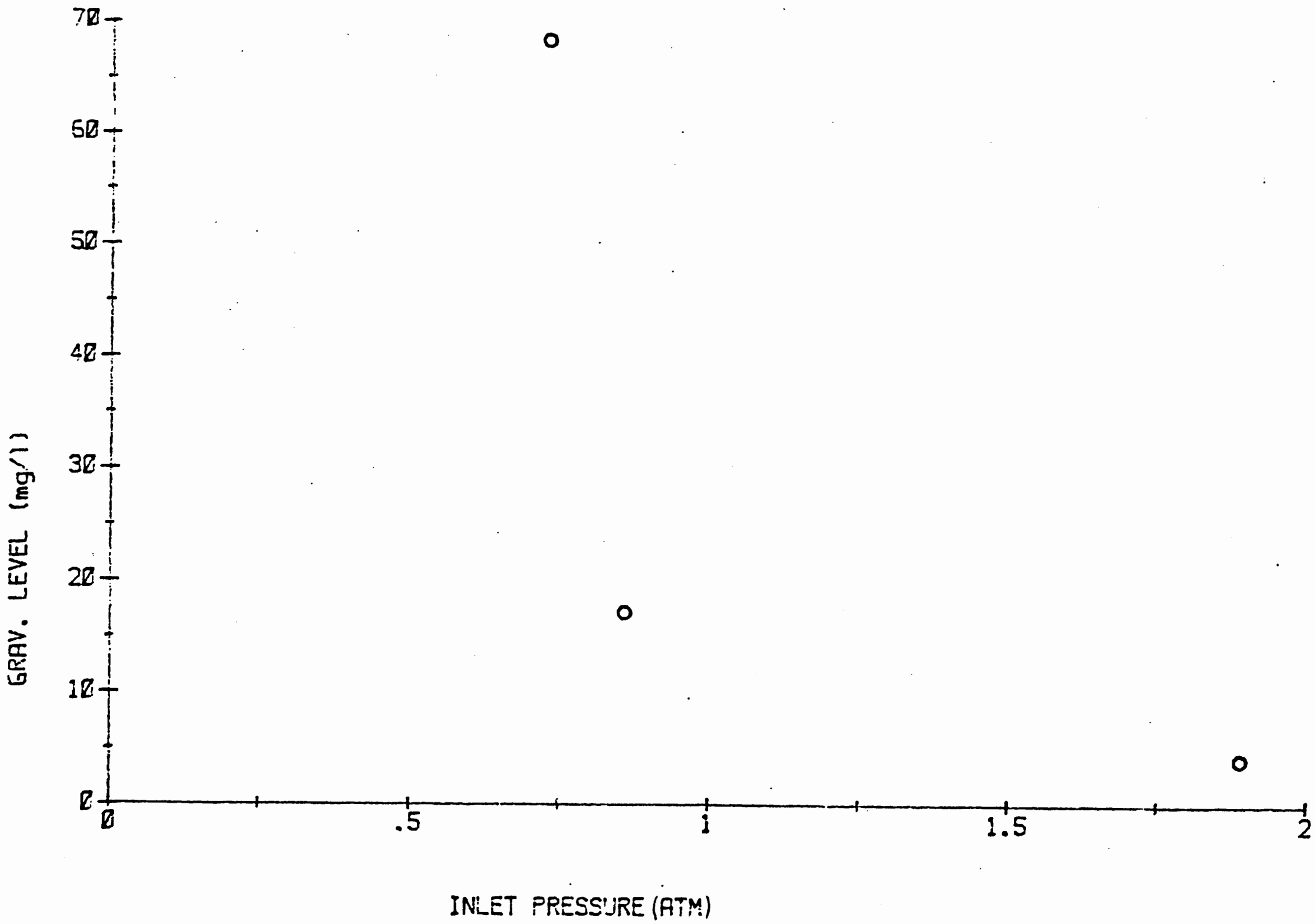


Figure 27. Fluid gravimetric levels - Cavitation wear - Pump 531

Adhesion Test

This test requires a variation of pressure to increase the asperity contact on the pump slipper and subsequently to increase friction and wear. The tests were conducted at normal conditions - 2500 psi (no asperity contact), 500 psi (some asperity contact), and 200 psi (more asperity contact). The degree of contact can be measured through the increased mechanical efficiency of the pump. Table I presents the results of overall volumetric and mechanical efficiencies obtained for the test pump.

Figure 28 presents the results obtained in adhesive wear. Comparing with normal wear, the abrasivity of adhesive wear is not significant. Similar results were obtained using particle counts (Figure 29). Although some large particles were present in the system, they were not large enough to generate abrasive wear which is characterized by the generation of very small particles. Besides, in this type of pumps adhesive wear is obtained at low pressure. At low pressure the clearances of pumps are larger than a high pressure. Smaller clearances are more susceptible than large clearances to abrasive wear.

One important fact obtained through this experiment is that in this type of pump design, the wear produced at low pressure is equal to or slightly higher than the wear produced when the pump is operating at normal conditions (Figure 28). This finding is very important, taking into account that it is widely accepted that low pressure can

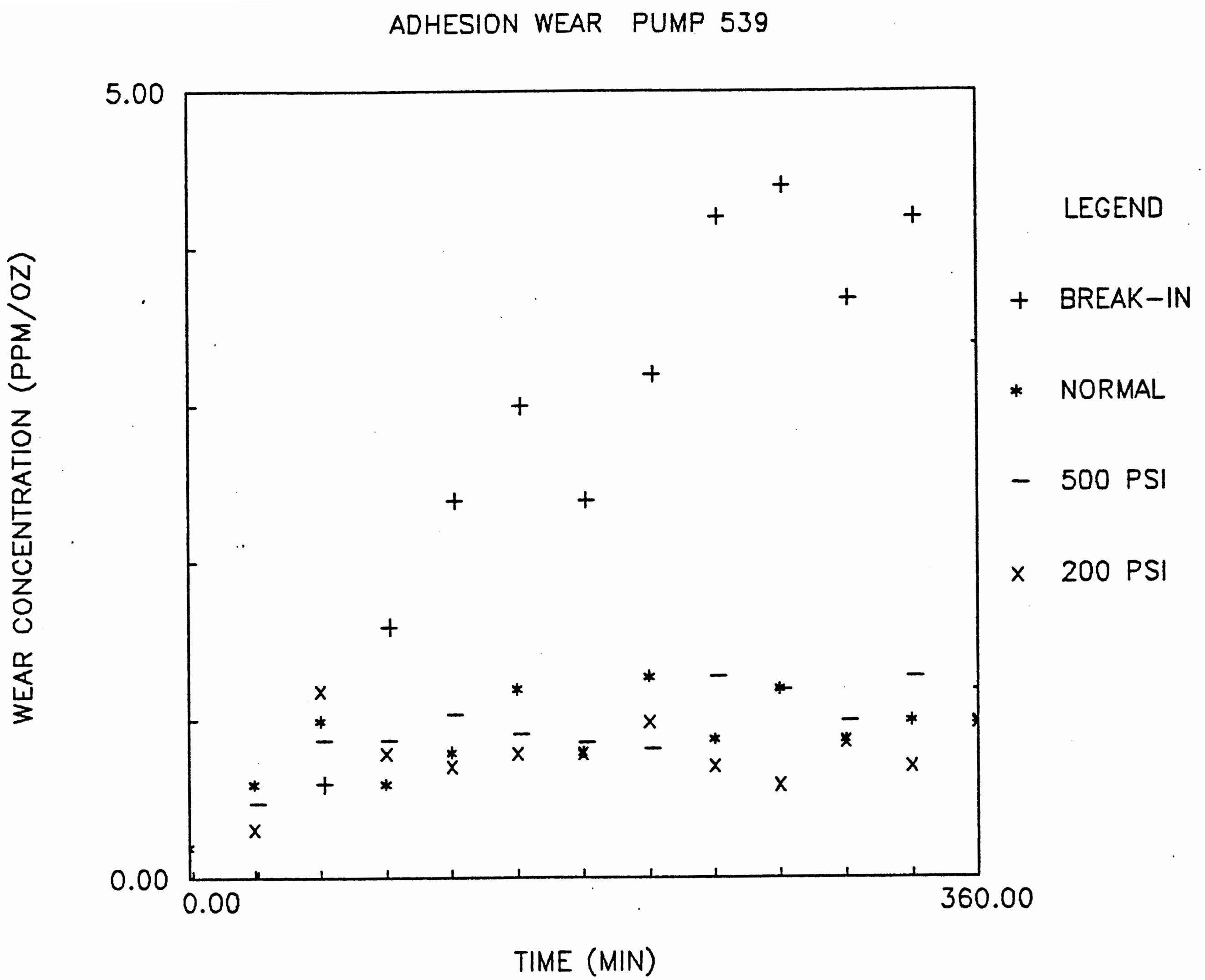


Figure 28. Magnetic wear debris generated under adhesion conditions

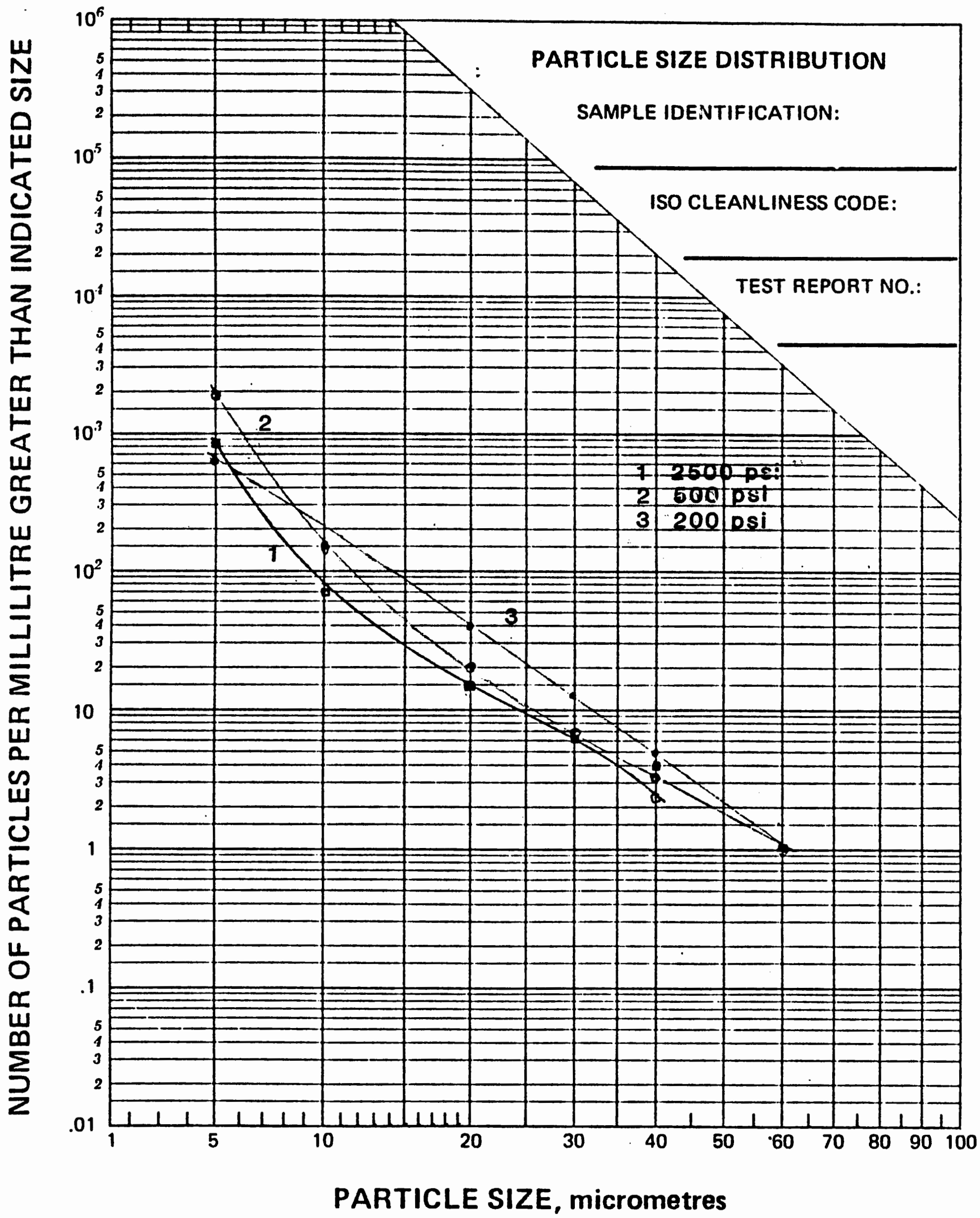


Figure 29. Particle size distribution obtained after six hours of testing. Adhesion wear - Pump 539

prolong the life of a pump. It has been observed by the investigator that when external particle contaminants are added in high concentrations to an axial pump operating at very low pressure, a breakdown of the slippers is detected after several hours.

The results of adhesive wear also show no significant difference between 500 psi and 200 psi. At 500 psi, asperity of the two sliding surfaces comes into contact and a smoothness of the surface begins. The asperity contact does not increase significantly when the pressure is further reduced to 200 psi (Figure 28, 29); in fact, it is reduced. Thus, experiments including adhesion tests were done at 500 psi.

The wear produced under pump break-in is also shown in Figure 28. Break-in procedure relates to adhesive wear in the gradual smoothness of internal surfaces. The wear concentration produced by break-in wear is significant as is shown in Figure 28. After the break-in procedure was performed the pump generated characteristic wear of normal operation.

Corrosion Test

The effects of different concentrations of water in the system are shown in Figure 30. These corrosion tests were conducted after the pump had been soaked in fluid with the same water concentrations for twenty-four hours. The time was arbitrarily selected to simulate water condensation of

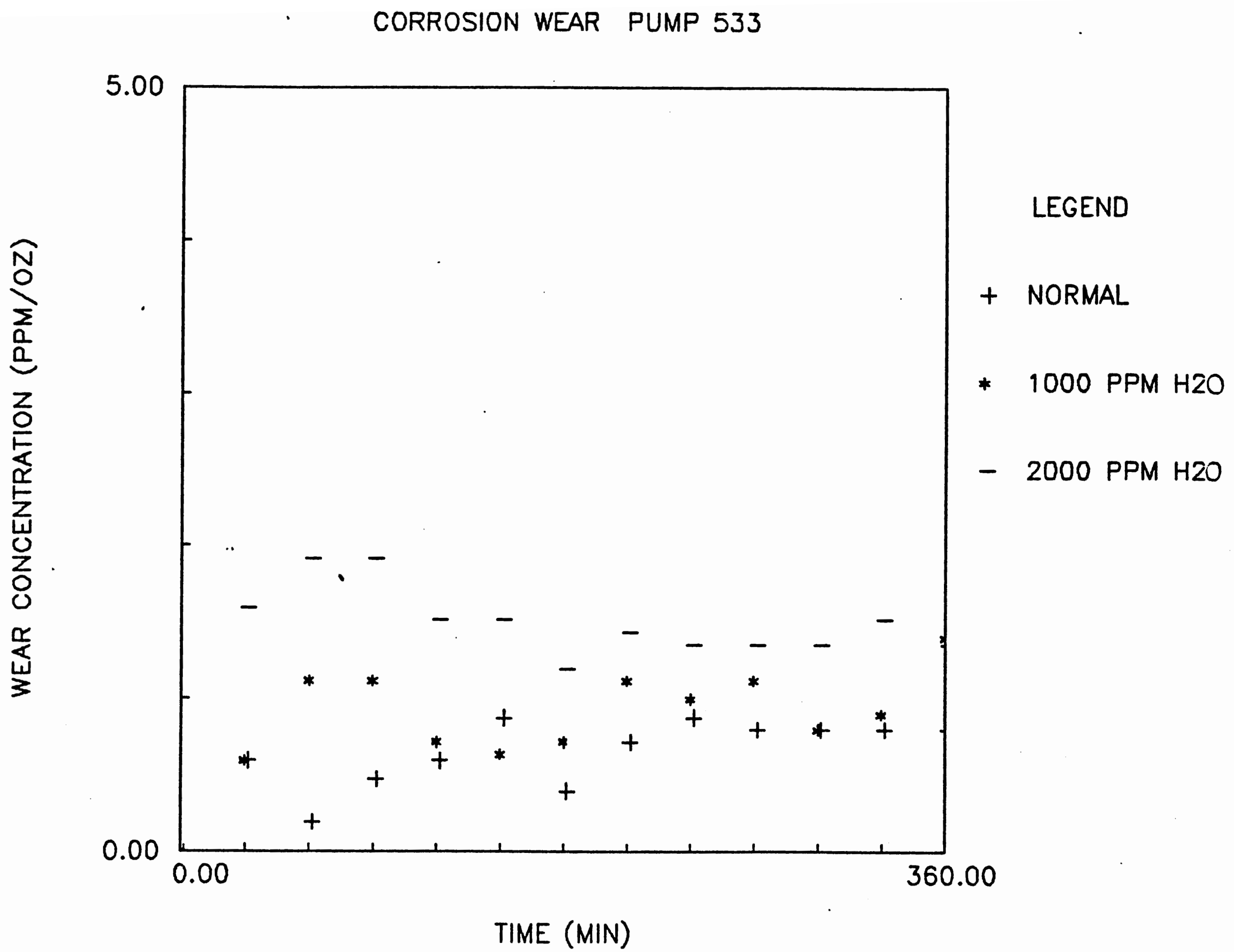


Figure 30. Magnetic wear debris generated under corrosion conditions

stop and start conditions experienced by hydraulic systems in field operation.

The effects of corrosion wear shown in Figure 30 on pumps depicts a variation on the wear generation rate at the beginning of the test. This sudden wear acceleration and deceleration in the wear process to reach the steady state can be explained as the effect of rapid removal of the oxides built-up during the soak time. After the oxides were removed, the new surface was oxidized again, but this time the oxides were smaller because of the short time of growth allowed before their removal.

The steady-state levels of wear concentration in the system increased with increasing water concentration. Similar results were observed in the particle and gravimetric analysis shown in Figures 31 and 33. The wear increased due to the combination of higher particle generation of the corrosion mechanism and its abrasive effects. The wear gravimetric levels shown in Figure 33 indicate that dangerous gravimetric levels (54 mg/l) are reached with high levels of water concentration present in the system. Clean systems are characterized by fluid gravimetric levels below 10 mg/l. Systems with gravimetric levels above 40 mg/l are considered very dirty.

Adhesion-Cavitation Test

The combined effect of adhesion and cavitation did not alter the normal wear process of the pump (Figure 33). The

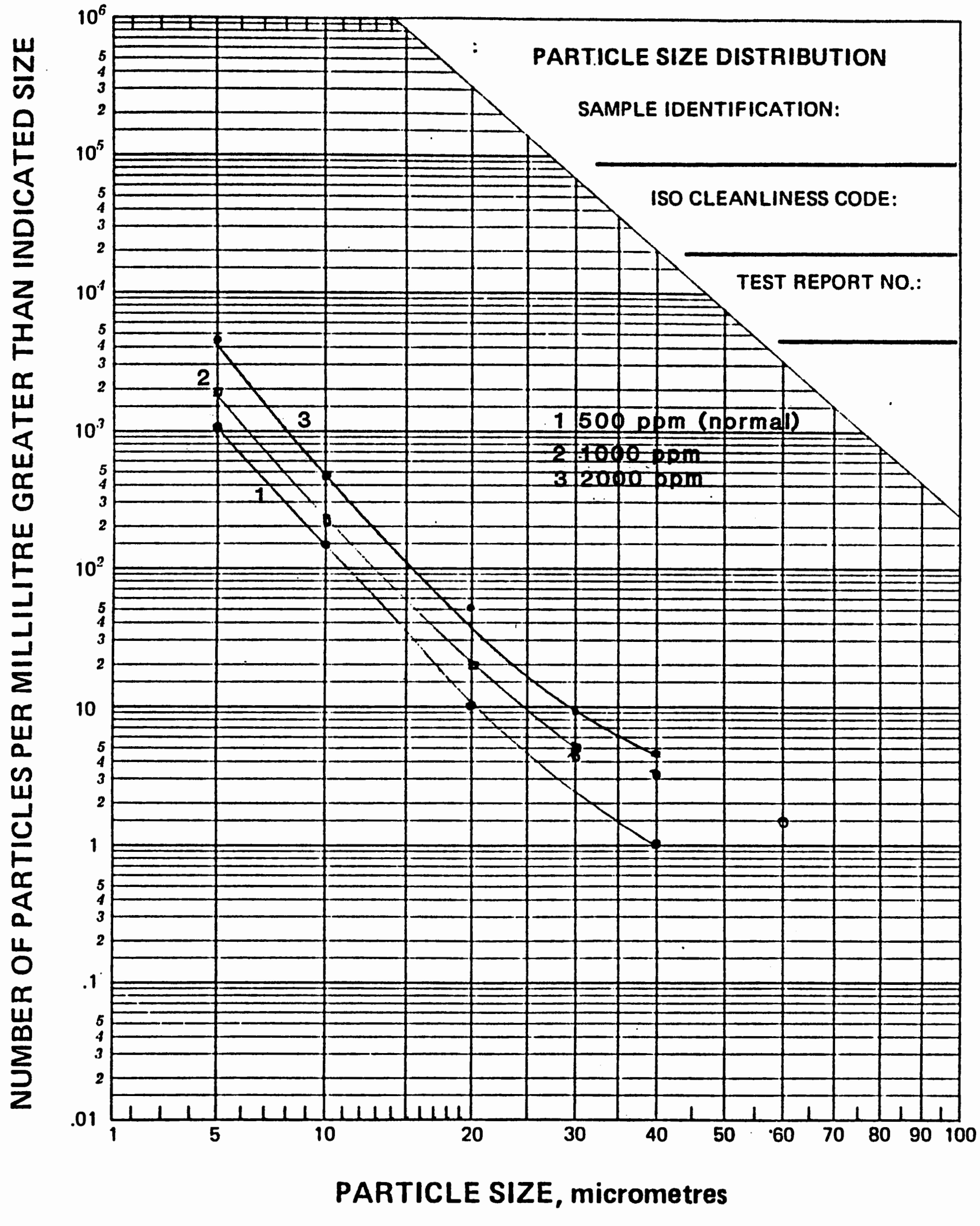


Figure 31. Particle size distribution obtained after six hours of testing. Corrosion wear - Pump 533

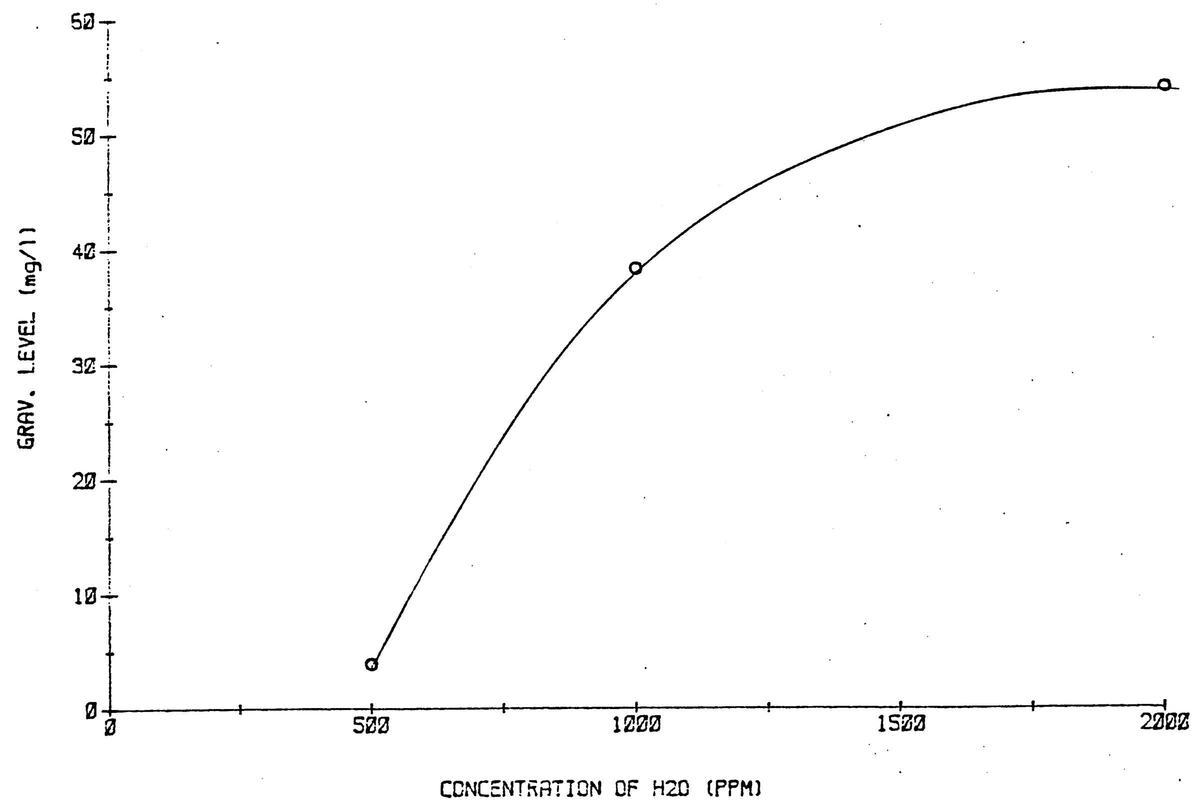


Figure 32. Fluid gravimetric levels. Corrosion wear pump 533

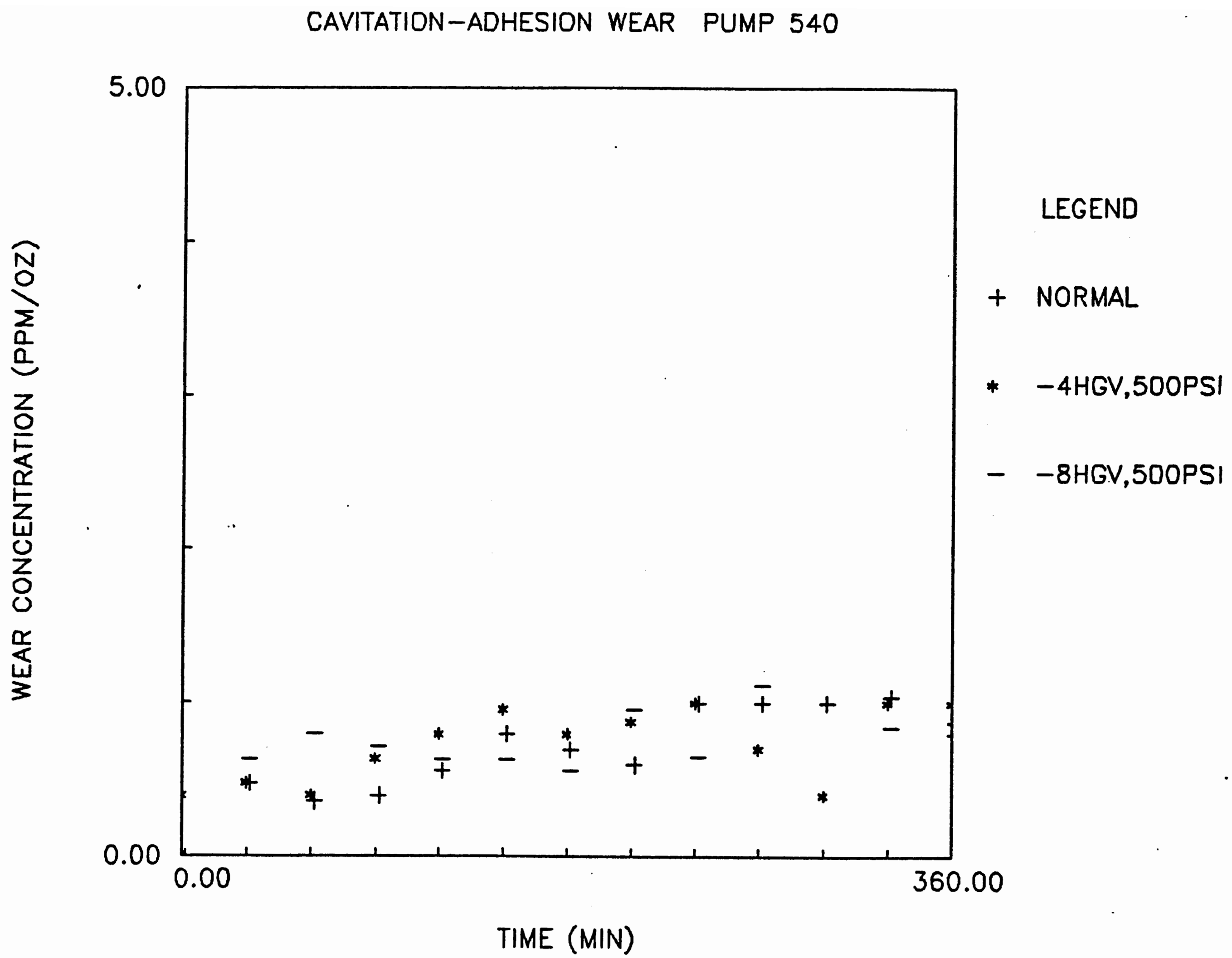


Figure 33. Magnetic wear debris generated under cavitation-adhesion conditions

effects of clearances and low pressure previously discussed are also important here. Thus, smaller concentration of smaller particles was observed (Figure 34). Factors changing in this experiment were clearances and pressure. In previous experiments they have been held constant. Furthermore, it is difficult to establish dependency on the wear effects. The cavitation effects on stressed vs. relaxed material can also be a factor influencing wear generation and should be investigated further.

Corrosion-Adhesion Test

The combined effects of adhesion and corrosion are more evident than those of adhesion-cavitation wear (Figure 35). However, when comparing Figure 30 with Figure 35, it can be seen that corrosive wear effects are more dominant than adhesive wear. The balance of adhesive and chemical wear is presented in Figures 36 [69]. For a given severity condition, adhesion prevails over corrosion under low concentration of reactive lubricant and corrosion over adhesion under high concentrations of reactive lubricant. The similarity of the particle distribution between corrosion wear (Figure 31), and corrosion-adhesion wear (Figure 37) suggests that corrosion is the dominant wear mode for the corrosion-adhesion test.

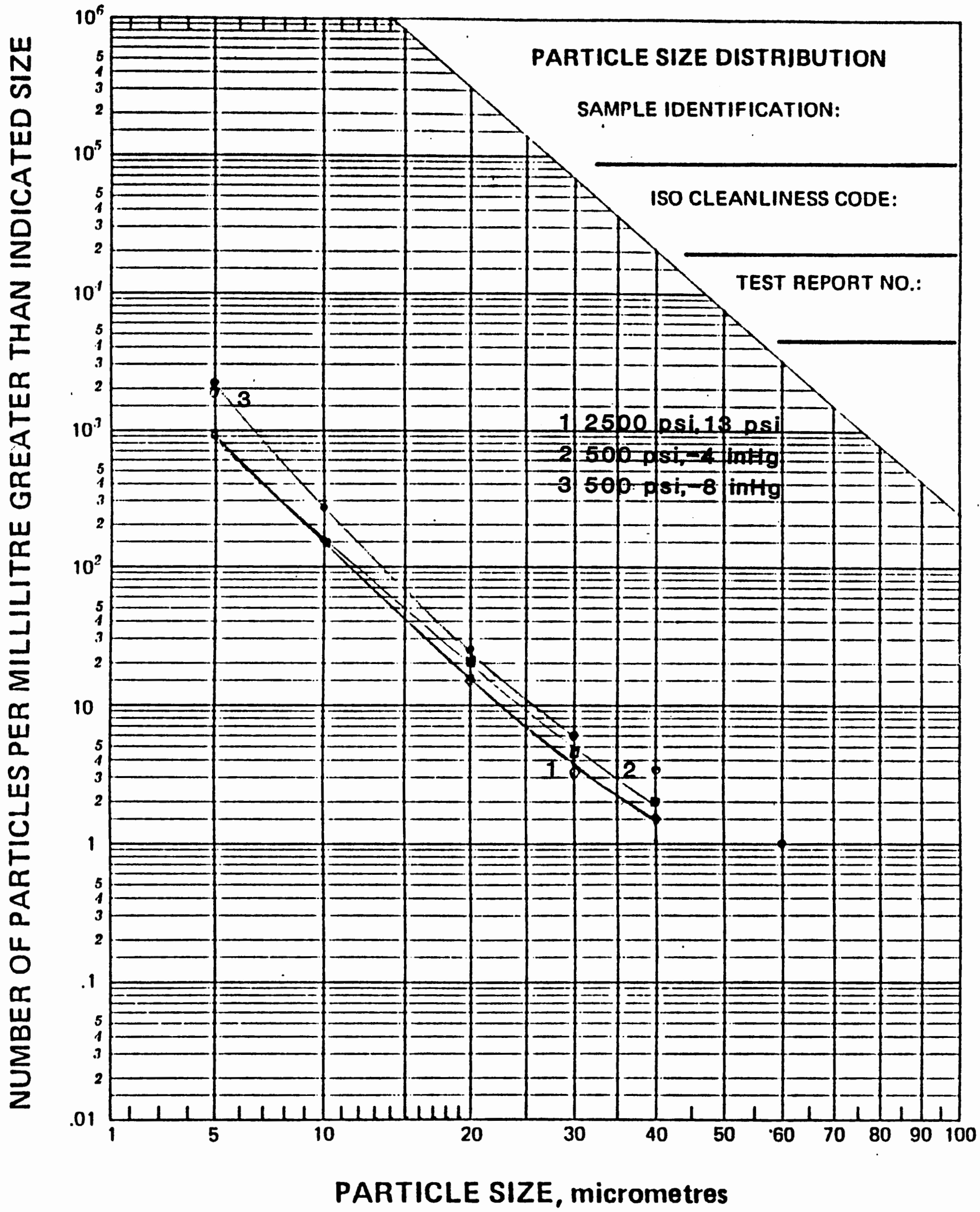


Figure 34. Particle size distribution obtained after six hours of testing. Adhesion-Cavitation wear - Pump 540

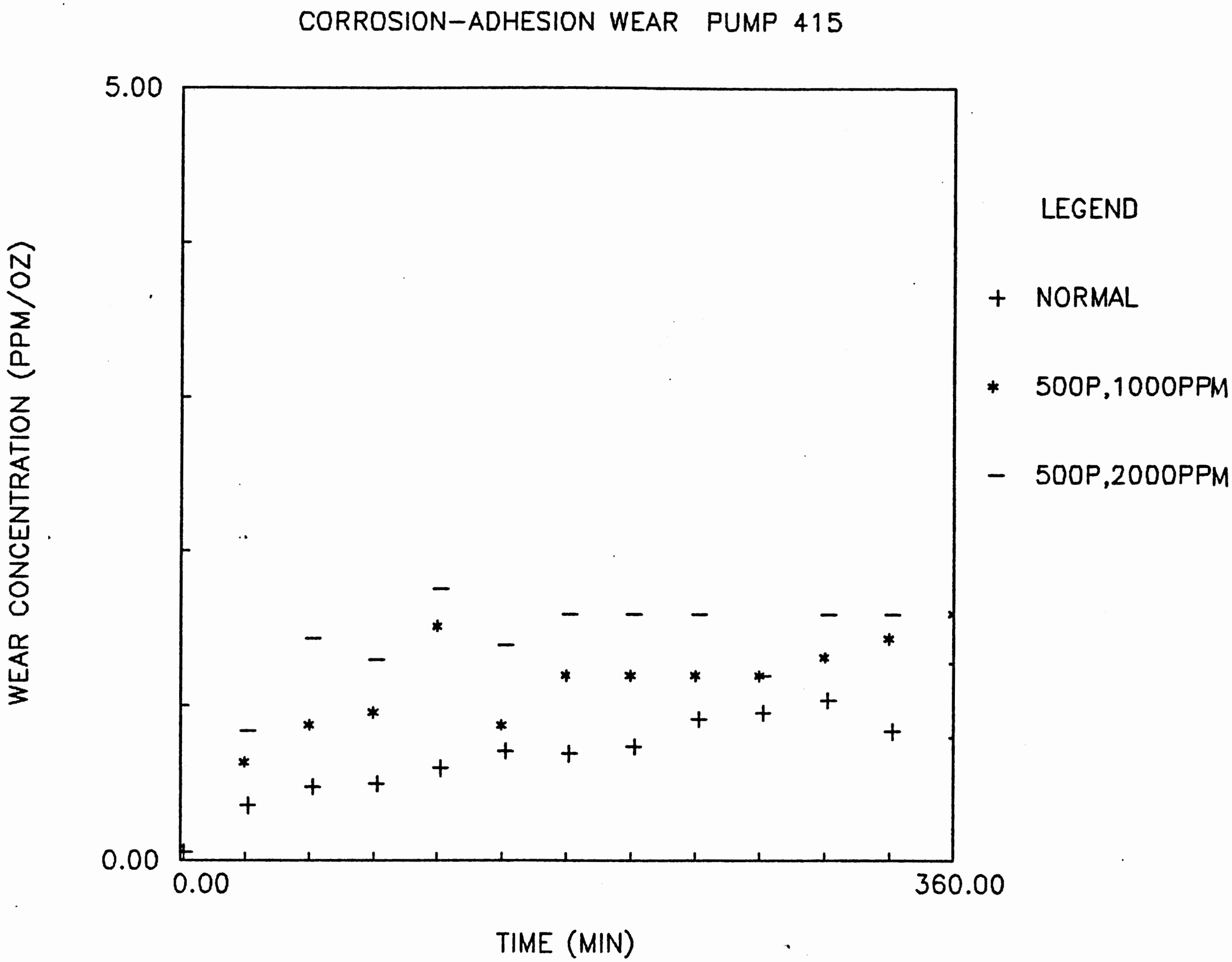


Figure 35. Magnetic wear debris generated under corrosion-adhesion conditions

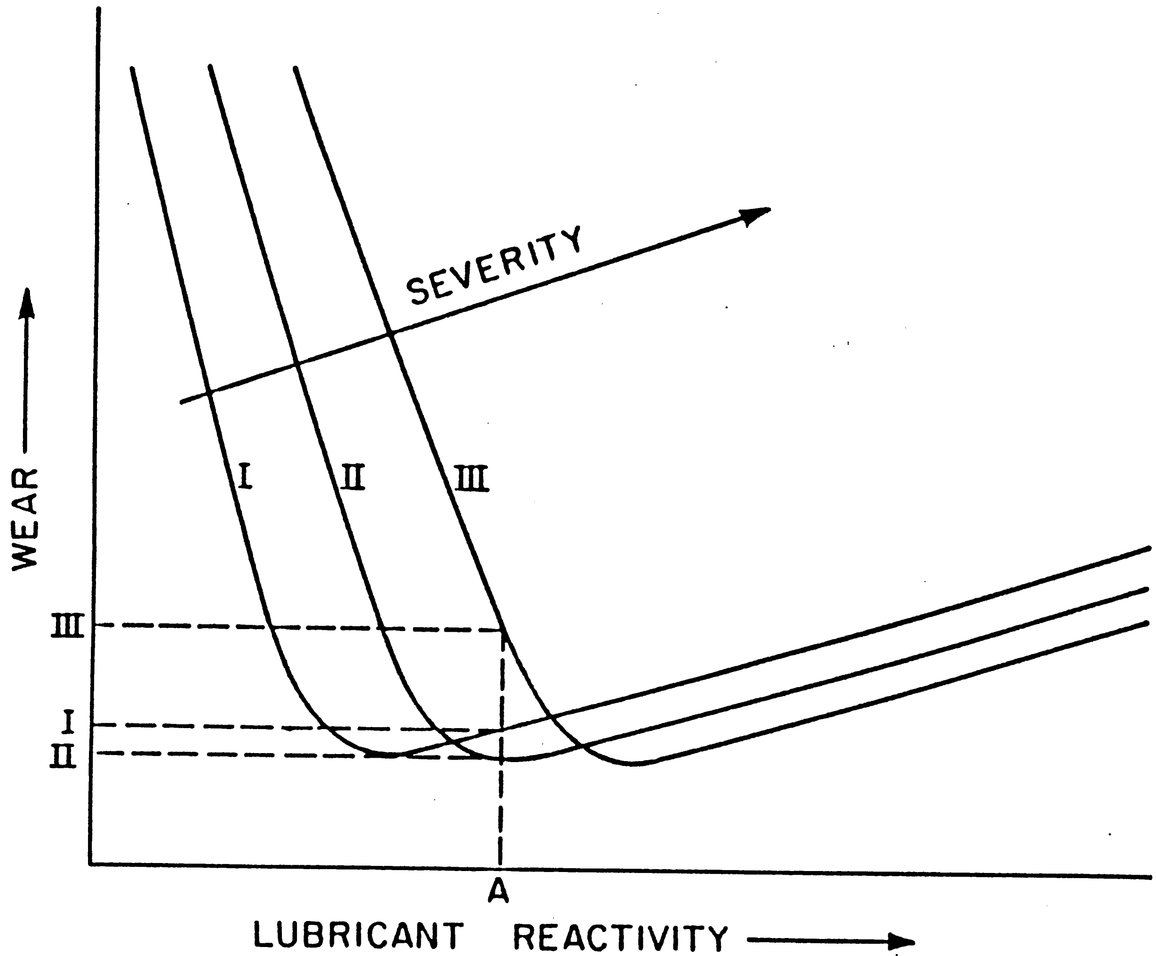


Figure 36. Schematic illustration of the severity of of sliding on adhesive-chemical wear balance

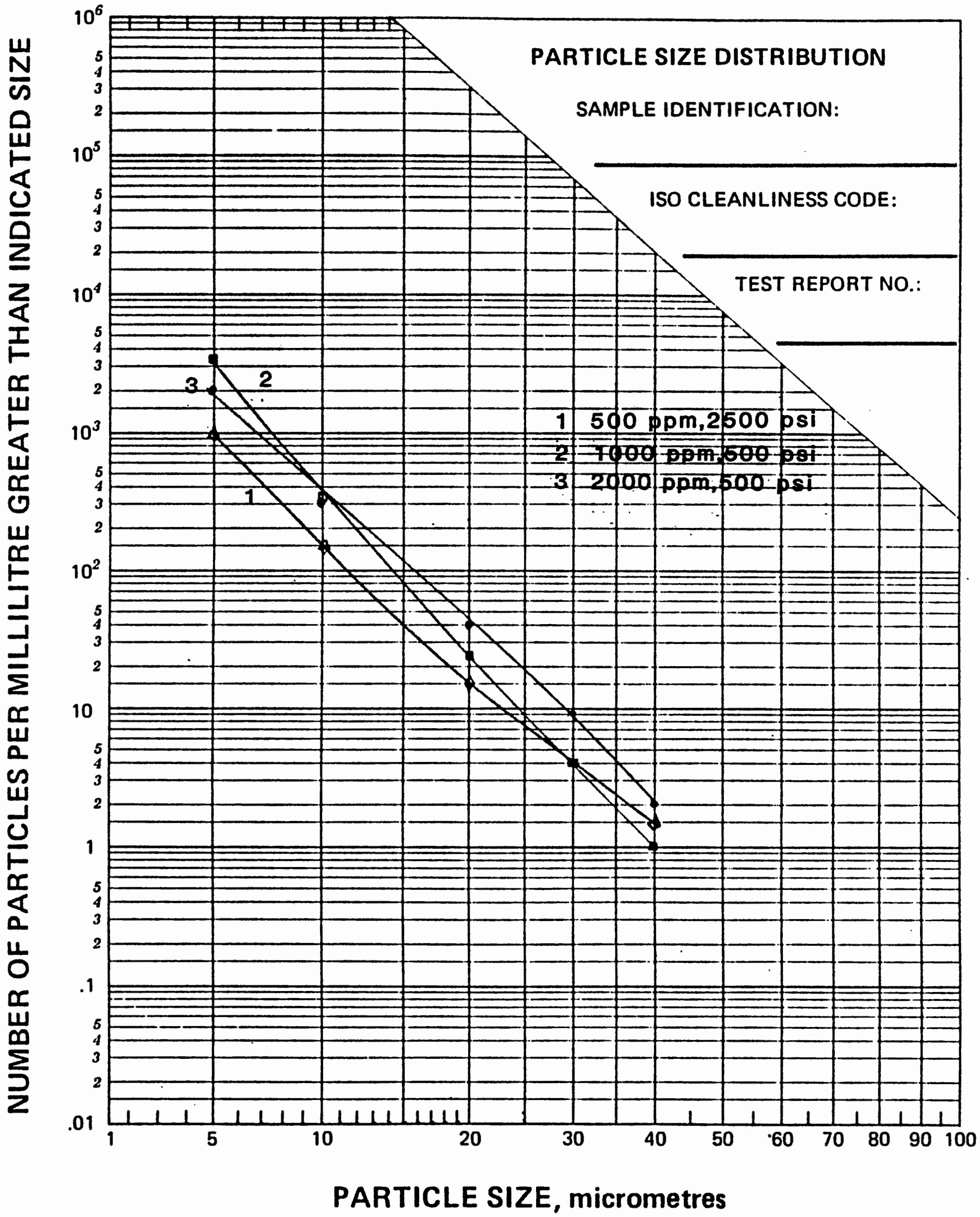


Figure 37. Particle size distribution obtained after six hours of testing. Corrosion-Adhesion wear - Pump 415

Corrosion-Cavitation Test

A representative sample of synergism is observed when corrosion and cavitation are combined. Figure 38 shows the results of the drastic effect of cavitation on wear concentration for a given concentration of water. This effect is a cooperative effort between cavitation and corrosion. Cavitation effects break the lubrication film damaging the material surface. At the same time passage is also allowed for the oxygen dissolved within the fluid to diffuse into the material causing oxidation. This continued synergistic effect weakens the material. Furthermore, long-wear particles are produced by cavitation and corrosion combinations (Figure 39). Large concentrations of particles are observed in this test at different sizes suggesting the enlargement of the pump clearances due to abrasive wear.

Further increases of water concentration do not necessarily increase the synergism between corrosion and cavitation (Figure 38 and 39). A super developed cavitation [39] was observed at 2000 ppm of water. Under this condition, the severity of cavitation decreases by damping effects created due to the presence of numerous bubbles in the system [39]. However, this increased cavitation is a transient phenomenon. It was observed that after 1-2 hours, the flow returned to the original cavitation operating point set for testing.

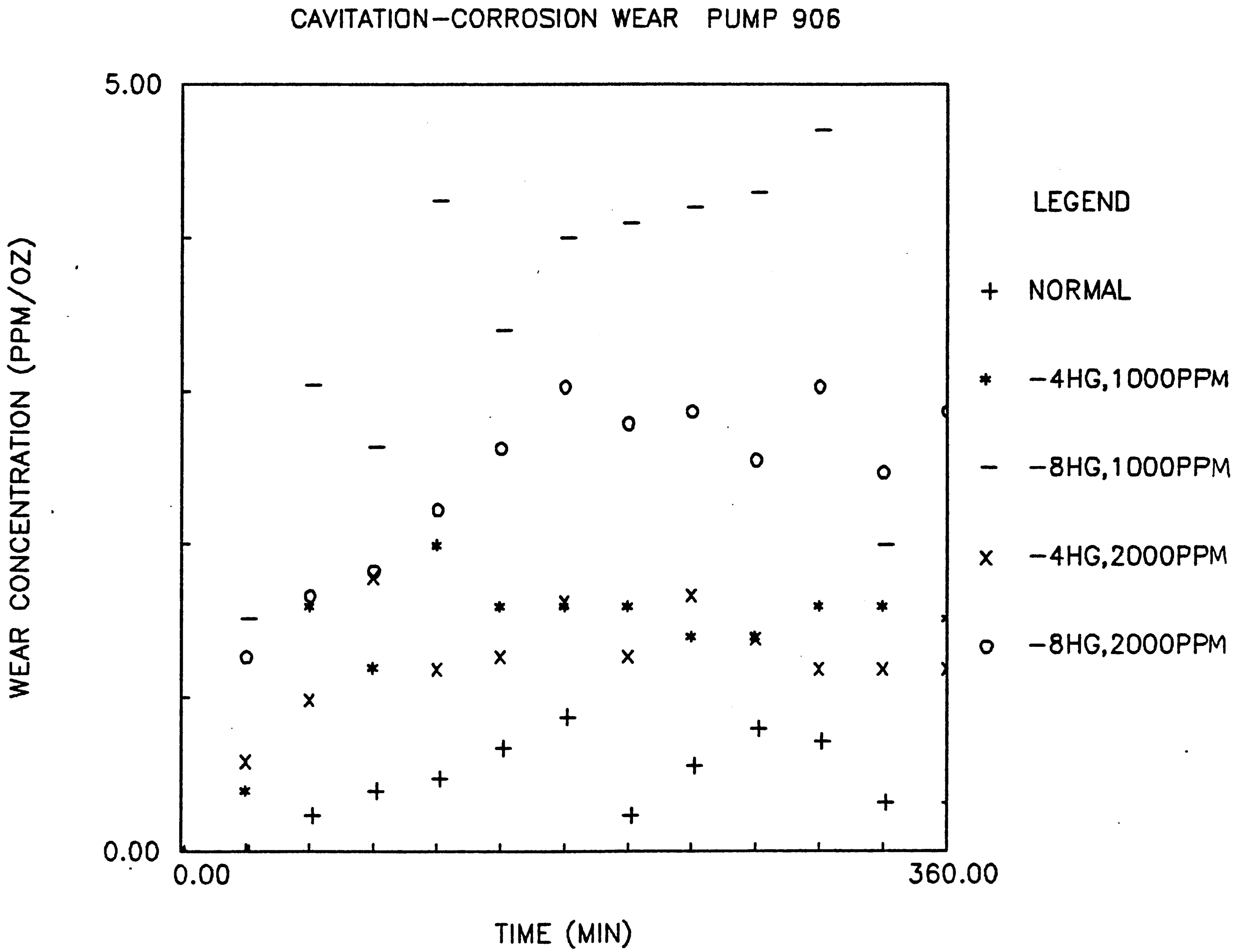


Figure 38. Magnetic wear debris generated under cavitation-corrosion conditions

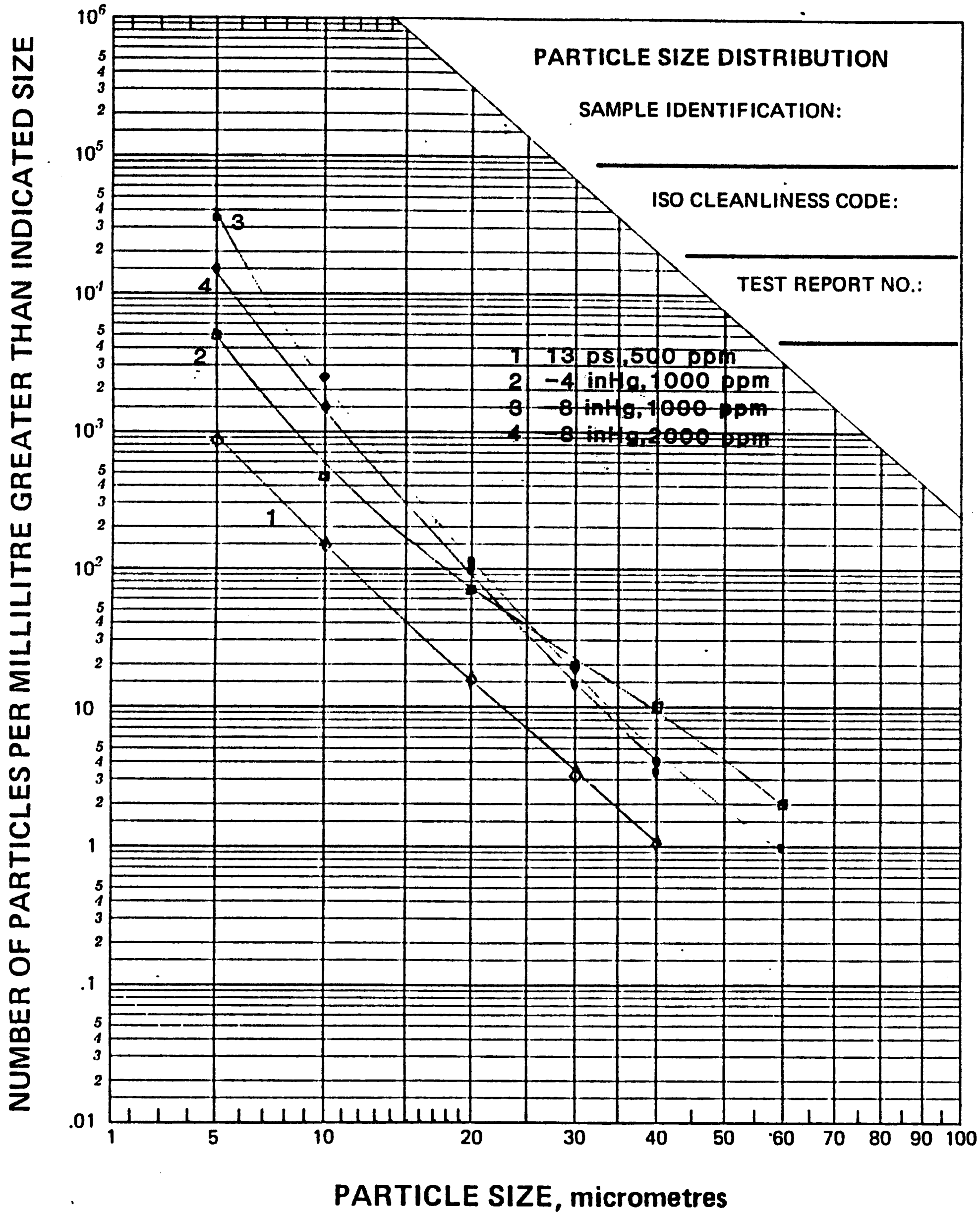


Figure 39. Particle size distribution obtained after six hours of testing. Cavitation-Corrosion wear - Pump 906

Corrosion-Cavitation-Adhesion Test

The combined effect of corrosion, cavitation and adhesion on pump wear are summarized in Figures 40 and 41. The contribution of adhesion in this synergism is negligible. As compared to previous results, most of the wear effects are due to cavitation and corrosion. However, the effect of low pressure tends to reduce the effectiveness of corrosion, cavitation and abrasion processes in generating wear.

Models Verification and Discussion

The theoretical relations established in Chapter IV to determine the influence of pump operating parameters on wear generation are compared with experimental data for verification. Empirical constants were determined using the least squares method. The fitness of proposed models to experimental data is discussed.

The synergistic wear produced by cavitation follows an exponential decay function given by Eq. (49). Figure 24 shows similar wear trends expressed in concentration units. The variation of the steady state levels of concentration of wear shown in Figure 24 is plotted in Figure 42 vs. inlet pressure. For a given time, Eq. 49 can be simplified to Eq. 53 and expressed in concentration units of parts per million by mass as shown below..

$$C_w = \frac{k}{(P_I - P_v)^m} \tag{53}$$

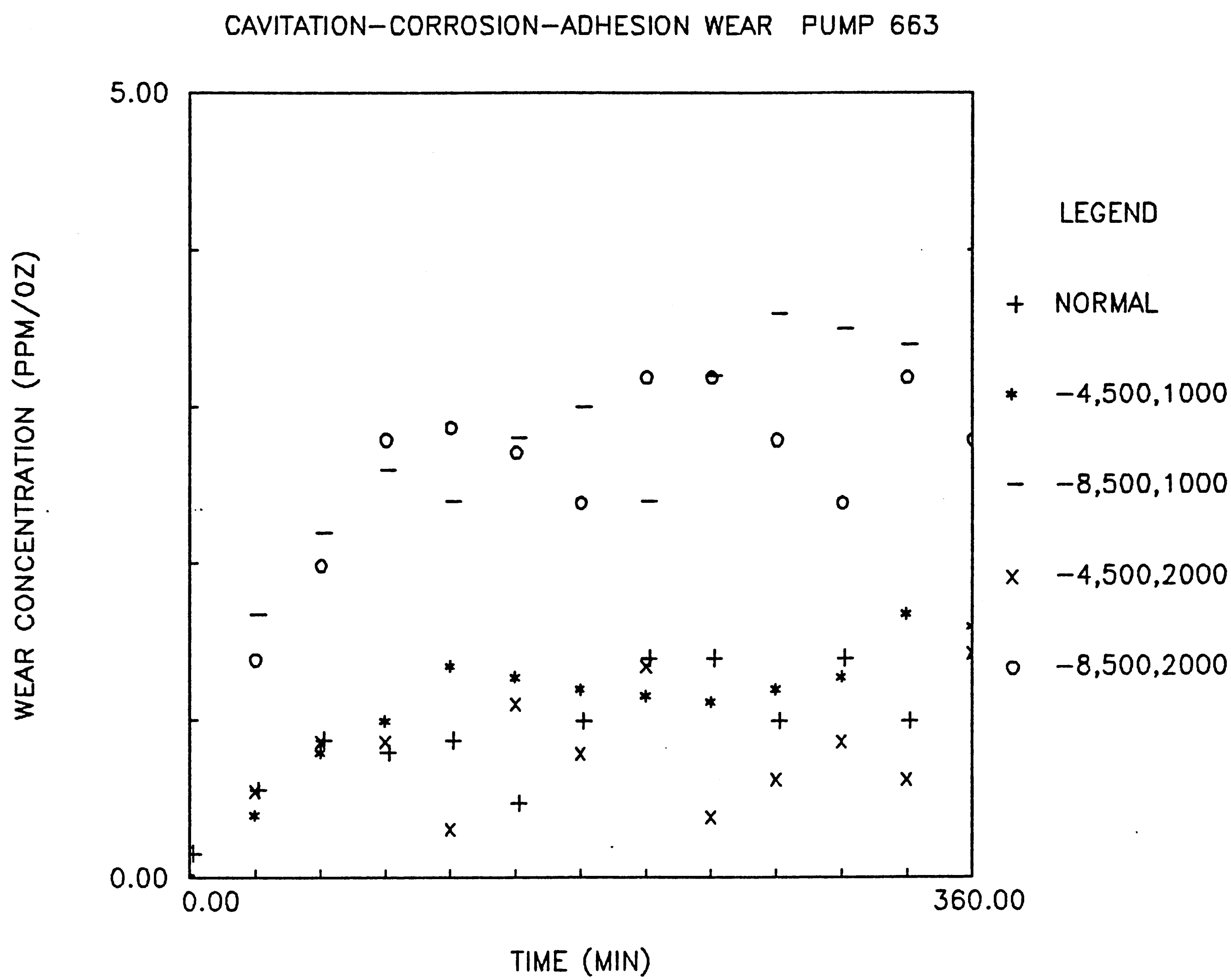


Figure 40. Magnetic wear debris generated under cavitation-corrosion-adhesion conditions

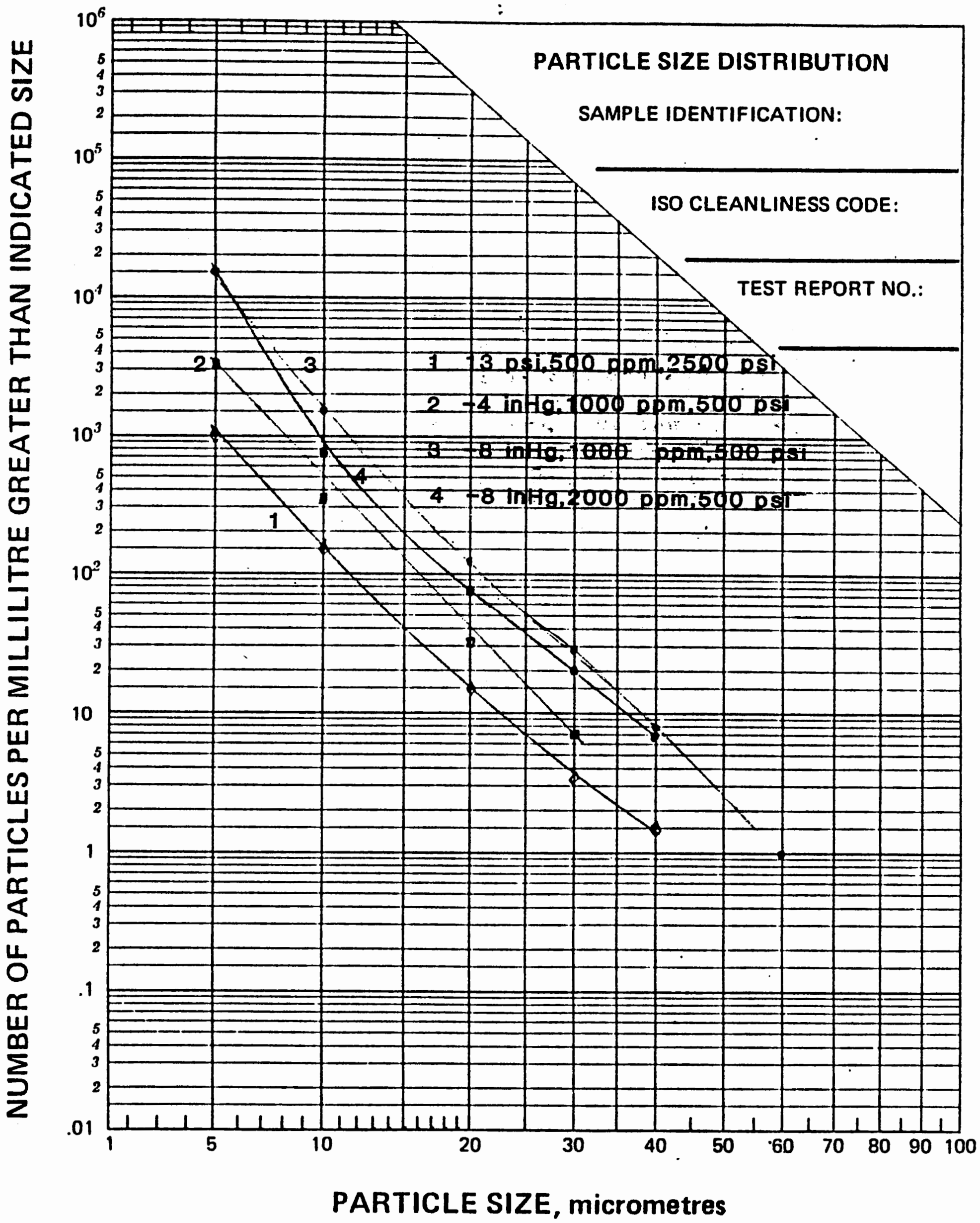


Figure 41. Particle size distribution obtained after six hours of testing. Cavitation-Corrosion-Adhesion wear - Pump 663

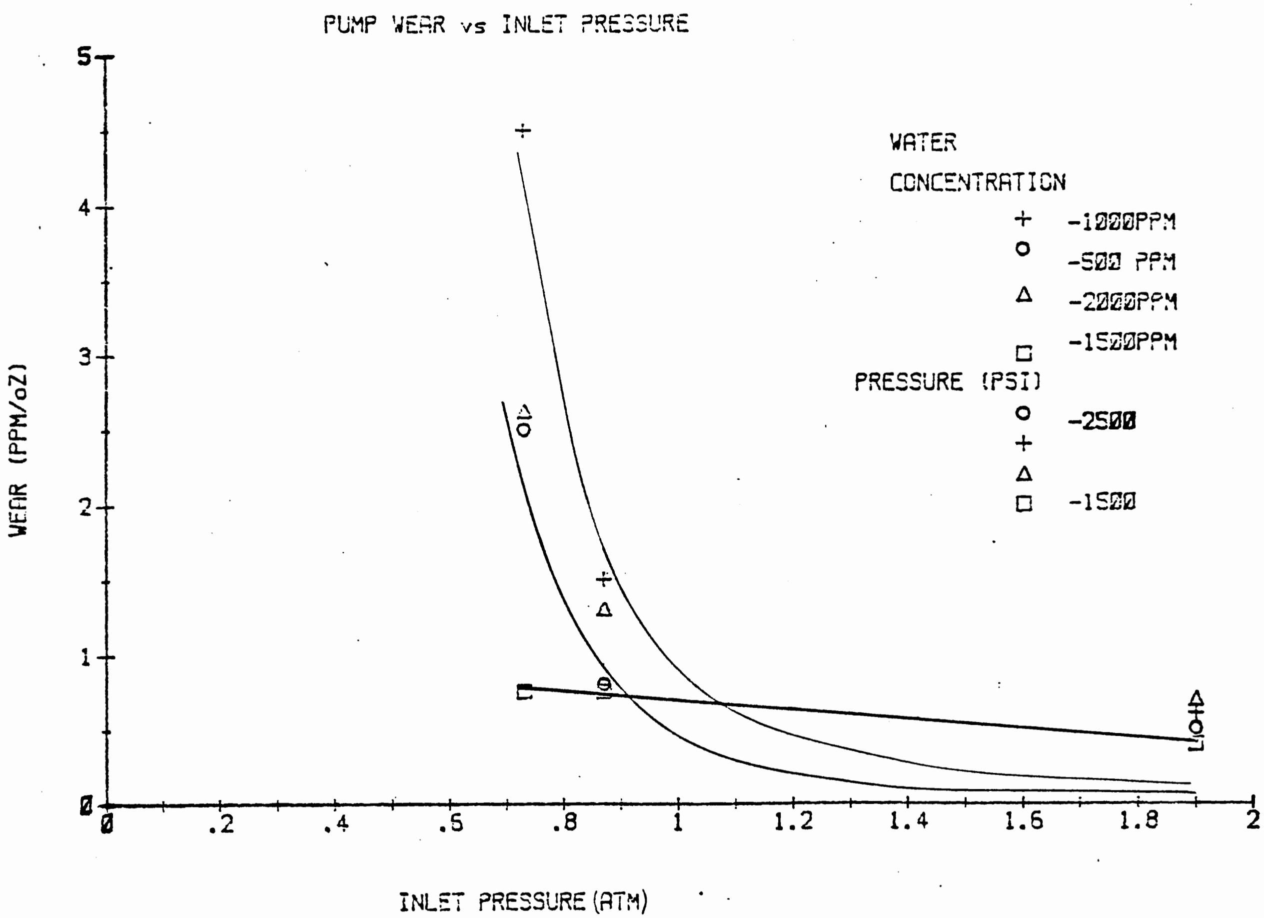


Figure 42. Wear concentration vs. Inlet pressure.

where C_W = concentration of wear

P_I = inlet pressure

k, m = empirical constants.

In Equation (53), when P_I approaches P_V, C_W increases considerably. In actual pump testing, P_I does not necessarily approach P_V,but 0.65 Atm as shown in Figure 12. This inlet pressure of 0.65 Atm is the pressure at which apor pressure is produced inside the suction chambers (Figure 12). Using a least squares method, Eq. (53) was fitted to the data. A model in the form of Eq. (54) is obtained

$$C_w = \frac{0.91}{(P_I - 0.65)^{1.43}} \qquad (54)$$

The model trend and experimental data are shown in Figure 24. The maximum error of 0.43 is observed at high inlet pressure. However, the proposed relation of wear which is inverse to the difference between inlet pressure and vapor pressure agrees with observed experimental results. When water concentration increases, the values of K and M in Eq. (54) change. K changes from 0.91 to 0.14 and m changes from 1.43 to 1.48. The variation in the constants suggests an interaction between the concentration of water and inlet pressure.

The variation of the steady state levels of wear concentration due to water in the system is plotted in Figure 43. At normal conditions of cavitation and adhesion,

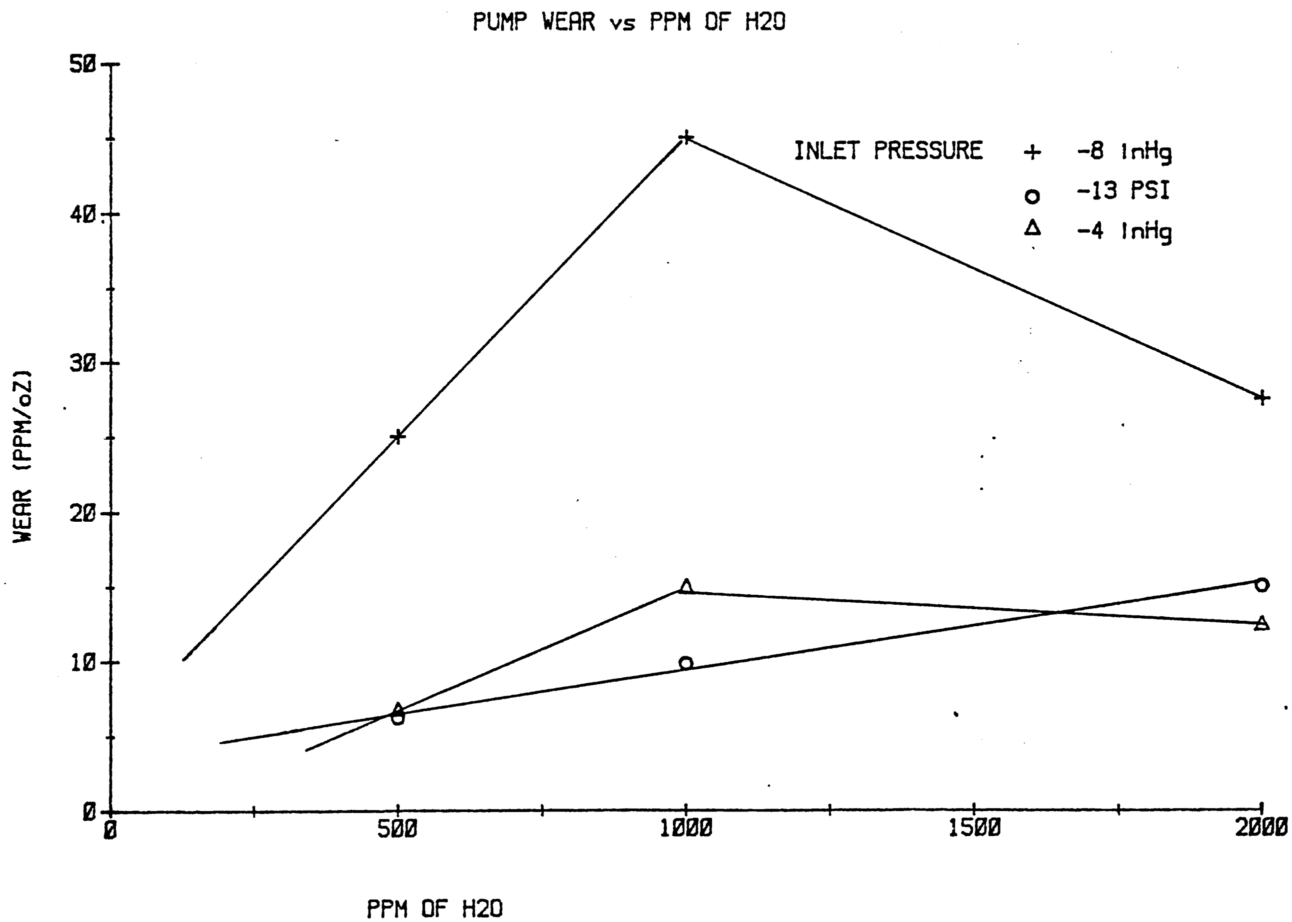


Figure 43. Wear concentration vs. Water concentration.

the variation of wear is a linear function of ppm. When a simplified form of Eq. (50) is fitted to data, a linear function in the form of Eq. (55) is obtained

$$C_w = 0.00055(PPM) + 0.4 \qquad (55)$$

where C_w = the concentration of wear (ppm/oz)

PPM = % of water in system volume

a,b = constants.

The linear relation shown in Eq. (55) has a correlation coefficient of 0.996. Similar linearity of wear vs. ppm is observed under normal and low levels of cavitation. However, the constants a and b in Eq. (55) change when cavitation is present in the system (Figure 43). If the cavitation effects were independent of corrosion, the slope observed under normal conditions should remain constant under cavitation conditions. Furthermore, synergism is occurring inside the pump as well as abrasive wear due to the presence of cavitation and corrosion. At high levels of cavitation, the low wear effects shown in Figure 43 are not predicted by any of the equations developed here. The reduced wear observed at high levels was explained earlier as damping effects caused by super-developed cavitation.

Insufficient data are available for a conclusive verification of the adhesive wear model; however, Figures 27 and 29 suggest the same trends proposed theoretically. Wear increases at low pressures.

The wear produced due to cavitation is not significantly affected by normal levels of water content and adhesive conditions. Eq. (52) suggests an increase of wear due to low system pressure. However, when deriving cavitation, wear system pressure was assumed constant in Eq. (4). When system pressure is reduced the velocity of bubble collapsing is also reduced (Eq. (4)). This impact force in Eq. (2) is low. A reduced effect on material removal due to cavitation is expected. Eq. (52) was formulated for the combined effect of wear modes. The second factor of Eq. (52) includes the interaction between all wear modes. When time t in Eq. (52) tends to infinity corresponding to steady-state, values of wear are obtained. However, the steady-state value depends on the levels of ppm, P_I and P. Furthermore, the proposed model and data suggest that when two or more wear models exist in a pump, their interaction changes the wear rate process.

In summary, the theoretical formulation of synergistic wear effects developed in Chapter I was experimentally evaluated in this chapter. The same trends suggested by the theoretical models were found experimentally. That is, independently of other modes present, cavitation wear depends inversely on inlet pressure.

Corrosion wear depends linearly with the water cavitation present in the system. Adhesion wear decreases with low system pressure. The adhesion was small compared with cavitation and abrasion wear. However, the adhesive wear model formulated here helps in the evaluation of the influences of variables such as design and pump operation which are important in the generation of adhesion wear. The results of experiments performed here suggest that when two or more wear modes are present, a synergism aside from the generation of abrasive wear occurs.

CHAPTER VI

CONTRIBUTIONS AND EXTENSION OF THE RESEARCH

This investigation opens new research avenues in the area of synergistic wear in actual machines. Through the study of synergistic wear effects in pumps, several interrelated mechanisms coupling pump design operation and environment can be better understood. In this chapter several insights gained from this investigation are presented and extended to the application of improving pump design operation and service life. The scope for further investigation of pump wear synergisms is also outlined.

Pump Wear

In this research, wear modes were identified, examined and diagnosed independently using actual pumps. The wear modes investigated here were induced by pump operation and design measured by the amount of wear debris being generated and examined by visual inspection of pump internal parts.

Effects of wear modes in a pump were evaluated as a whole. By measuring the total amount of wear, the combination of different synergisms present inside the pump are included. However, when examining the location of the damage caused by each wear mode, several facts became apparent. Each wear damage occurs on a different part of the pump. Cavitation damage was observed on the end of low port pressure of the valve plate (Figure 25). Adhesion wear damage occurs on piston slippers (Figure 16). Corrosion acts when materials are very dissimilar in electrical potential. In addition, each wear mode generates particles of different sizes and hardness (Table V) which will cause abrasive damage to different clearance size. There are three basic clearances in piston pumps. They are clearances of the port plate and cylinder barrel (6-12 microns), clearances between piston and bore (20-40 microns) and clearances between piston slippers and swashplates(2-4 microns) [70]. These clearances changed up to 20% due to variation in pressure and speed.

Although each wear mode acts on a different pump location, particles generated by each of them can create abrasive wear on any of the clearances mentioned above and changes in clearances also depend on the hardness or abrasive particles and the materials involved. Table VI summarizes the material hardness of the pumps used in this research. The hardness ratio of abrasive particles to contact material also determines the abrasive wear volume. For a given material hardness, there exists a critical value $H_{Metal}/H_{Abrasive}$ above which the wear decreases as shown in Figure 44-a [61]. When the contact material is very hard compared to the abrasive particle, the wear process decreases. This wear effect takes place because of the

TABLE V

TYPICAL PARTICLE SIZES AND HARDNESS GENERATED BY WEAR MODES

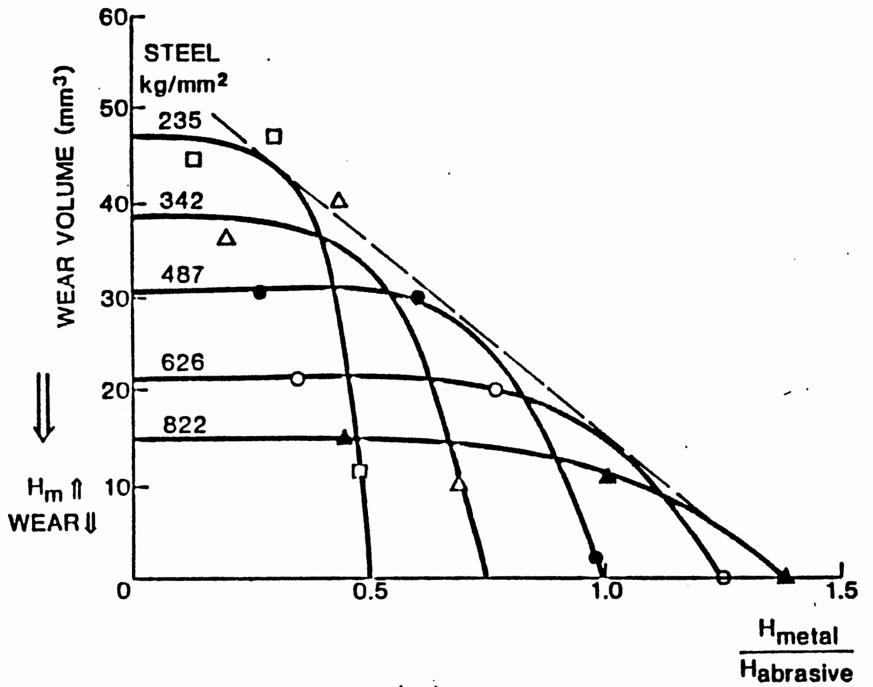
Wear Mode	Partical Size * (micron)	Hardness * (HB)
Cavitation	0-40 [22]	780
Adhesion	0-15 [24]	800
Corrosion	0-3 [25]	550
Abrasion	0-10 [28]	700

* Steel materials

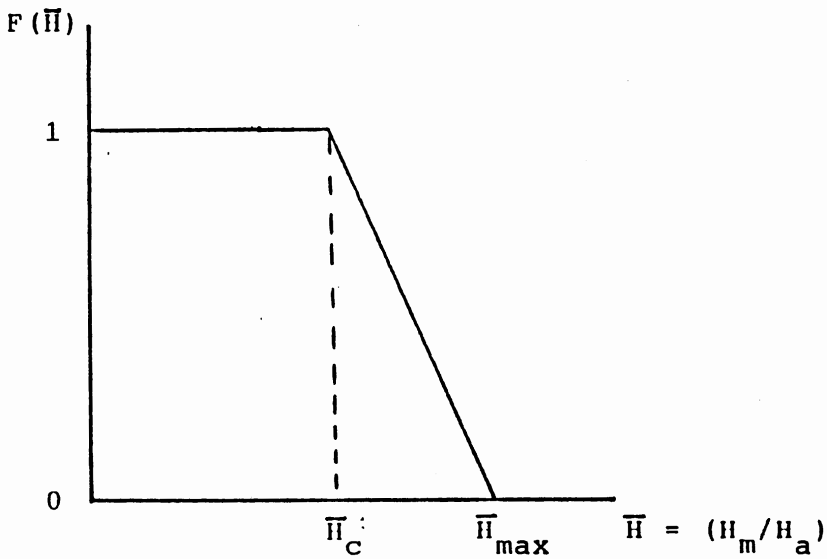
TABLE VI

HARDNESS OF PUMP MATERIALS

No	Part	Hardness (HB)
1	Swash Plate	520
2	Slippers	142
3	Piston	480
4	Bore	145
5	Port Plate	265
6	Piston Barrel	145



(a)



(b)

Figure 44. Effects of metal-to-abrasive hardness ratio on three-body abrasive wear.

plastic deformation or break-down of the abrasive particle instead of the indentation and plowing process characteristic of three-body abrasive wear.

When the abrasive particle is harder than the contact material, wear volume increases. However, the wear volume does not keep increasing the harder the particle. When the hardness of the particle to metal ratio approaches zero, the wear volume remains fairly constant. This effect occurs due to the indentation of the particle in the contact material without removing any wear material.

Furthermore, there exists a control value below which the wear is only a function of the metal hardness and independent of the hardness ratio. Above that value, wear decreases as Hm/Ha increases until Hmax as shown in Figure 44-b. Table VII summarizes the pump materials to abrasive hardness ratio. Then, through the identification and examination of wear modes described in this research a better basis is available to select materials, more resistance to either cavitation, corrosion, and abrasion damage and improved lubricating regimes to avoid adhesive wear.

Fluid Filtration

In this investigation, the particle size distribution for each wear mode was also examined. The particle size distribution obtained through sampling showed no particles larger than 50 - 60 micrometers. Although cavitation damage

TABLE VII

PUMP MATERIALS TO ABRASIVE HARDNESS RATIO

Wear Mode	Hm/Hq 1	2	3	4	5	6 *
Cavitation	0.66	0.18	0.62	0.18	0.34	0.18
Adhesion	0.68	0.12	0.60	0.18	0.33	0.18
Corrosion	0.94	0.25	0.87	0.26	0.48	0.26
Abrasion	0.74	0.20	0.68	0.20	0.37	0.20

* The numbers correspond to table V

has shown craters up to 80 microns in diameter, particles of such dimensions were not present in any of the samples during cavitation testing. In this research an assumption was made that particles of sizes close or equal to pump clearances exist only because pump clearances act as filters maintaining the maximum particle size around the maximum clearances present in the pump. Thus, if a known distribution containing particles of sizes smaller than pump clearances is injected into system fluid and a sample is taken after several minutes, the particle size distribution observed remains the same or increases up to the maximum dimensions of pump clearances. On the other hand, if distribution containing particles of size larger than pump clearances is injected into the system and a sample is taken after several minutes, the sampled distribution contains particles of dimension only up to the maximum enlarged pump clearance. Figure 45 presents experimental results obtained using a gear pump and ACTD distributions of 0-10 and 0-20 micrometers. Figure 45 shows supporting evidence for the assumptions made earlier. It shows how maximum particle size present in the systems varies and how pump clearances act as a filter of particles. Thus, samples taken during pump operation do not necessarily represent the true particle size distribution of a wear mode being generated, but only the size distribution controlled by pump clearances.

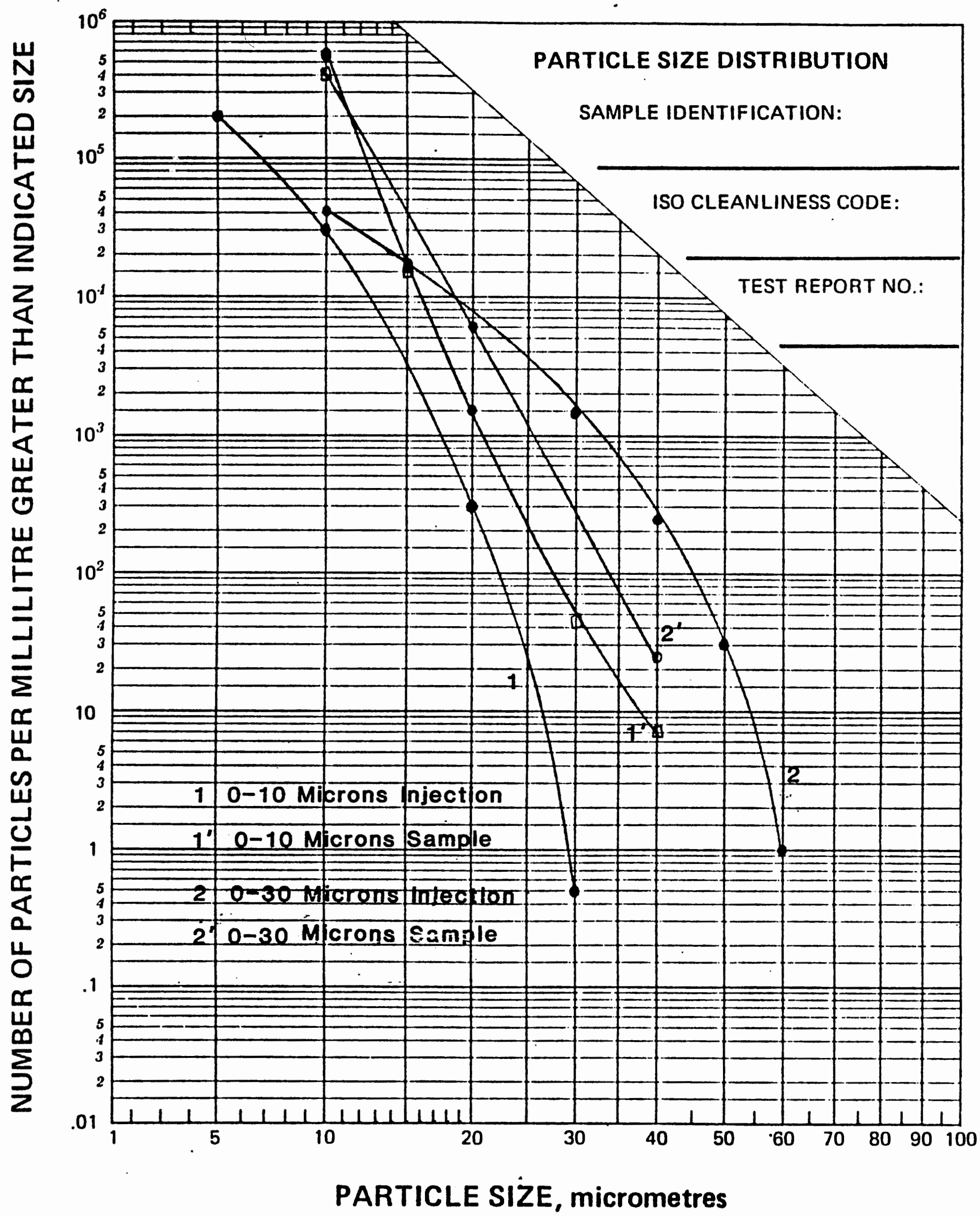


Figure 45. Particle distribution changes after injection in contaminant sensitivity tests.

Pump Service Life

In addition, this investigation shows the different wear rates generated by pump internal parts under specific wear modes. Wear rates are obtained from the curves that show the variation of wear concentration vs. time. Using wear rates, pump life can be predicted. Pump life is determined by reduction of pump output flow. In the experiments conducted in this investigation, cavitation wear causes a flow degradation of 0.7% after six hours and with 0.02% of water added, cavitation causes a flow reduction of 1.1%. The pump experiments conducted here are not accelerated pump wear type experiments. Furthermore, the flow degradation observed was minimum. However, with the wear monitoring methods employed in this research and test procedures, the testing time required to observe flow degradation can be reduced. In addition, the pump life obtained does not cause significant damage on the pump being tested.

There are parts in the pump that degrade without causing flow degradation, such as piston slippers. This type of adhesion failure can occur and be accelerated by the presence of small size particles without any indication of flow degradation. Then prediction of pump life should be made in the context of wear modes and their synergisms on pump internal parts.

Scope for Further Work

This investigation initiated the study of wear synergisms in pumps. The methodology used in this research can be applied to wear synergisms of any other machine. Wear generation in machines is an indication of the operating condition, wear mode and design effectiveness. In order to more effectively apply the results of wear synergisms to the prediction of machine service life, further study of the following topics is required.

1. The true particle size distribution of each wear mode should be obtained in order to closely predict abrasive wear.
2. With the identification of particle size distribution for each wear mode, better pump diagnostic techniques can be implemented.
3. Wear synergisms need to be evaluated over a wider spread of severity levels in order to establish break points or saturation conditions.
4. The variation of the wear rate obtained under a combination of different wear modes should be further investigated. The interacting effects between two wear or three wear modes should be established. This will allow detection and control of the dominant wear mode in the pump.

5. Other type of wear synergisms should be examined. For example, the inclusion of ingested particles in the system accelerates any ongoing wear mode present in the pump.
6. The work presented here provides grounds for filtration study of the basis of wear generation instead of particle ingestion.
7. Other fluid power components can be studied under wear regeneration and wear synergisms. The information acquired will constitute better filtration selection for the whole hydraulic system.

CHAPTER VII

SUMMARY AND CONCLUSIONS

Summary

This thesis examines the synergistic wear produced by cavitation, adhesion, corrosion and abrasion in hydraulic pumps. The objective of this research is to study each wear mode independently and to establish theoretically and experimentally the synergistic wear produced in a pump.

Wear modes have been individually recognized and defined. They can also be rigorously analyzed independently through the basic mechanism of interaction between surfaces in contact under load and motion. However, in a machine element, the overall wear results from the interdependent operation of several of these mechanisms, either sequentially or simultaneously (synergism).

Wear modes in pumps can be observed and characterized from operation of pumps. These wear modes are the effects of individualistic factors strongly influenced by the pump operation mode. The synergistic effects of four distinctive wear modes are analyzed. The wear modes are cavitation, corrosion, adhesion, and abrasion. These are the most common wear modes present in pumps. Although cavitation, adhesion, and corrosion exists independently, their synergism in pumps generates abrasion which occurs when wear particles of a similar dimension to the pump's internal clearances are generated by each of the wear mode pass through these clearances. For this reason, each wear mode is investigated in conjunction with abrasive wear.

The nature of the cavitation, adhesion, corrosion and abrasion wear modes is examined. Each wear mode possesses a trigger factor or stressing object which accelerates the wear process. For cavitation wear, the stressing object is the impact jet; for adhesive wear, asperity contact; for corrosive wear, oxide film growth or corrosion rate; and for abrasive wear, particle size. The wear process for each mode shares two basic mechanisms - elastic and plastic deformation at different levels. The common characteristic in all wear modes is the final product - wear debris.

The volume of wear generated by each wear mode is formulated independently. An estimation of the damage caused by these wear modes is made through a theoretical mode. Finally, the total amount of volume generated is estimated by the addition of the two above-mentioned models. A model for the total amount of wear obtained under combination of two or more modes is also proposed in conjunction with abrasive wear. The use of these wear modes was derived generically and then related to pump parameters for evaluation.

Seven pumps were used in the experiment for the evaluation of the independent and combined effects of cavitation, adhesion, and corrosion. A specially designed experimental program was used. Each wear mode is identified by a specific test procedure. The severity of the tests is varied using the inlet pressure for the cause of cavitation, water content level for corrosion, and system pressure for adhesion. The wear debris produced by each of these wear modes was monitored through wear analyzers, particle analysis and gravimetric analysis methods. Finally, the theoretical formulation of the wear model is correlated with the experimental results obtained. A discussion and an extension of the study to pump wear, fluid filtration, and service life is made. Suggestions for further study are also presented.

Conclusions

After investigating the synergistic effects of pump wear theoretically and experimentally, several important conclusions have been drawn. The major accomplishments and conclusions of this research are enumerated below.

1. Cavitation, adhesion, corrosion, and abrasion wear modes can exist independently, but their synergy in pumps causes abrasion wear.
2. Wear models for each wear mode were developed independently. They predict the amount of wear generated as a function of the trigger factor or stressing object that accelerates the wear process.

3. Identification of pump wear modes was made through an analysis of pump design and operation.
4. Wear models were related to pump operating and design parameters. This includes the relation of the trigger factors of wear modes to actual pump parameters.
5. A synergistic wear model for cavitation, adhesion, and corrosion was developed. This model includes the abrasion effects of cavitation wear.
6. A synergistic wear model for the combined effect of cavitation, adhesion, and corrosion was developed.
7. An experimental program was formulated for pump wear modeling, identification, and testing. These tests included the selection of the correct pump operating condition for induction of wear modes and the qualification of equipment for wear debris monitoring.
8. Cavitation wear was found to be inversely proportional to the difference between pump inlet pressure and the vapor pressure of the fluid as the synergistic wear model indicates.

9. Cavitation damage was observed on the port plate of the pump on the high pressure releasing grooves.

10. Cavitation damage increases with system pressure. No significant damage was observed at low pressures.

11. Corrosion wear, as the model indicates, varies linearly with the water concentration level in the fluid. The corrosion wear process tends to stabilize faster than any other wear mode.

12. The combination of corrosion and cavitation produces the maximum wear recorded in conjunction with abrasion wear. Their interaction increases wear generation.

13. Cavitation wear is reduced under the presence of high concentration of water.

14. Adhesive wear occurs at low pressures due to the asperity contact between piston slippers and the swash plate. This statement was theoretically modeled and experimentally verified.

15. When adhesion is combined with cavitation and corrosion, the effects of corrosion are more dominant.

16. Pump life should be established on the basis of the synergistic effect of pump wear instead of depending on flow degradation.

17. The adhesion wear mode does not manifest itself as flow degradation.

18. Particle size distribution of a wear mode cannot be obtained through a sample taken of a system fluid when a pump is present in the system.

19. Pump clearances control particle size distribution. Maximum particle size is dependent on maximum pump clearances.

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2

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