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STUDY OF FILTRATION MECHANICS AND SAMPLING TECHNIQUES

CONTRACT: NAS 8 11009

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CHAPTER I

GENERAL INTRODUCTION

The Fluid Controls and Systems Center at Oklahoma State University has been working with NASA personnel at the George C. Marshall Space Flight Center (Huntsville, Alabama) with the expressed purpose of establishing a scientific basis for solving problems related to filtration mechanics and fluid contamination. The studies conducted prior to the current contract period have been concerned mainly with methods for appraising and evaluating filtration media. A great amount of effort was well spent in developing reliable test procedures and measuring techniques. Specifically, phases have been directed toward wire cloth filter media, fluid sampling techniques, vibration effects on filtration, and fluid contamination monitoring and measurement. In retrospect, it appears that the direction of the research was correct and sound. The contributions made as a result of this work have been widely acclaimed, and the spirit of cooperation exhibited by industry has expressed their gratitude to NASA.

This report summarizes the details and results of the research conducted under Phase IV of Contract NAS 8 11009. The actual work accomplished during the reporting phase has required a reorientation of thoughts and objectives to permit the establishment of a contamination control criteria based on the contaminant tolerance of components. In fact, for the purposes of establishing a proper test philosophy for both filtration performance and contaminant tolerances it has been necessary to re-examine the basic concepts of expressing contamination levels.

The specific areas of study which were pursued during the current contract period were the following:

1. The establishment of a physically meaningful cleanliness level criteria for fluids which expresses in quantitative terms the contamination level.
2. The filtration characteristics of filter media as exemplified by their effect on contamination levels.
3. Expressions for the contaminant tolerance level of components in terms of a rigorous cleanliness level criteria.
4. The performance and specification of depth type filter media as they are related to the physical parameters of the matrix.

A strong background has been established by the results of the work reported herein which will permit a realistic approach to the problems in contamination control. It is a hopeful trust that the knowledge gained through the referenced research will in turn be of service to the sponsoring agency and to the industry at large.

CHAPTER II

CONTAMINATION LEVELS AND CONTROL

2.1 INTRODUCTION

A significant understanding has been acquired during the referenced contract period regarding the general area of contamination levels and control. It is reasoned that this understanding is the direct result of the development and verification of techniques to obtain quantitative information in this area. In retrospect, it is difficult to explain why many of the concepts in fluid contamination are just now being recognized. The fact remains, however, that the many hundreds of seemingly useless test results which have been obtained over the past few years are beginning to be significant. Certainly there is less "lost motion" and fewer mistakes in judgment.

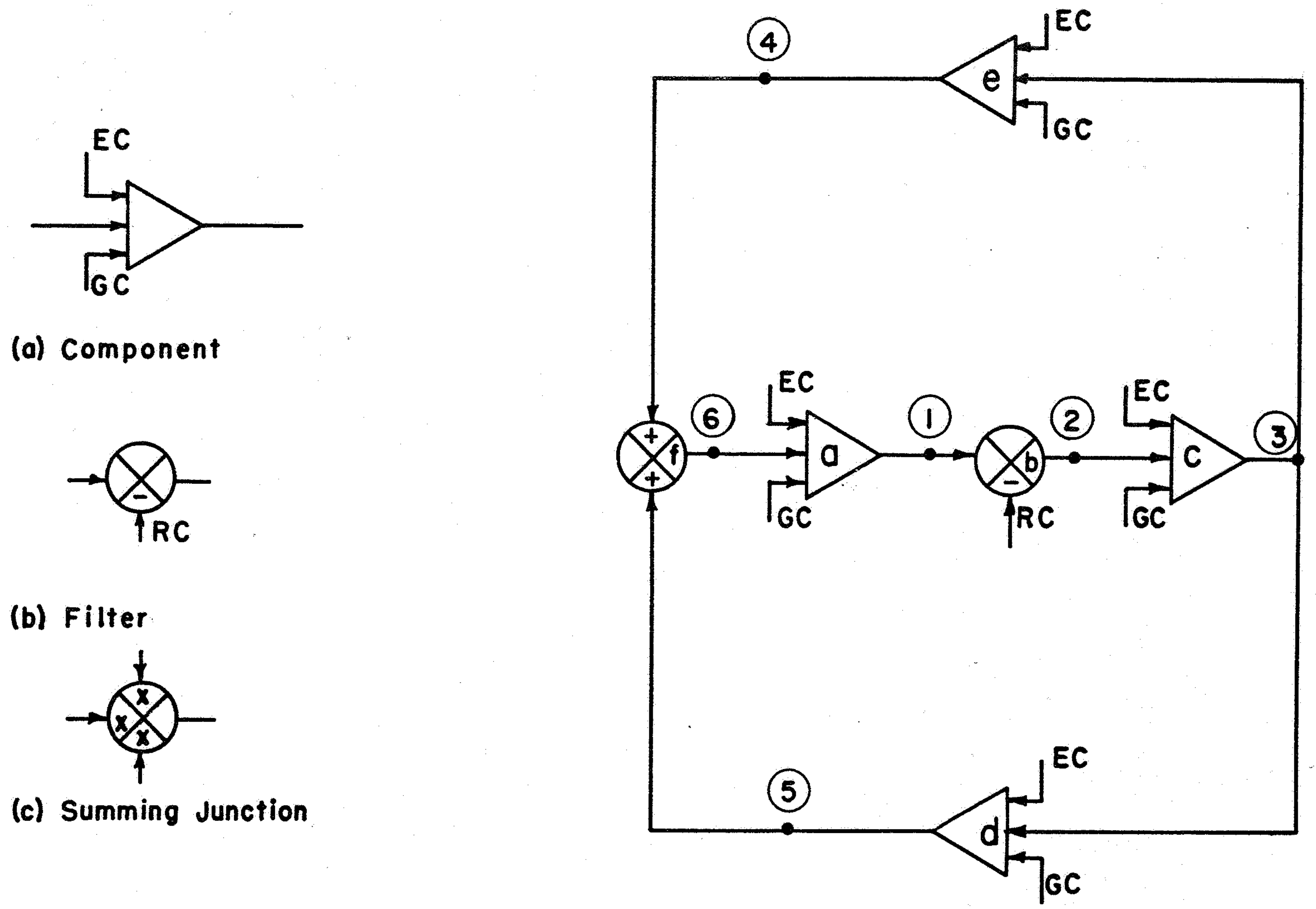
Since this contract has been integrally involved with the relation of filtration mechanics to the specification of component contaminant tolerance levels, a great need was recognized for a mathematically rigorous and physically meaningful method of expressing contamination levels in fluid systems. Such a method demanded that quantitative values be applicable to the performance characteristics of filters and the contaminant sensitivity of components. This chapter is concerned with the development and presentation of such a method and its utilization in contamination control.

2.2 THE DYNAMIC APPROACH

The dynamic approach to system contamination levels is believed to be a unique and accurate way of describing the influence of components on the characteristic contamination levels in a hydraulic system. It has been recognized that a contamination level obtained from one point in a system does not necessarily reflect the overall state of the contamination level of the system. Consideration must be given to the effects of components and environment on the respective levels within the system. This is to say that as the fluid flows through various components, the contamination level (when transient effects such as sloughing can be ignored) changes due to infiltration, generation, and filtration conditions.

Consider the schematic block diagram of a typical system shown in Fig. 2-1. Three types of symbols are required to represent the components in the block diagram system as illustrated in Fig. 2-1. Component symbol (a) represents a pump, valve, hose, actuator, reservoir or any group of such components which exhibit generation and/or infiltration actions. The filter symbol (b) represents the only component considered to be capable of removing contaminant from the system. The summing function (c) characterizes the connection of parallel branches in the system.

In reference to Fig. 2-1, the contamination level at point b is fed into component (a) which may generate contaminant "GC" by its associated operation and may permit the infiltration of contaminant "EC". Therefore, if representative fluid samples were extracted at points 6 and 1, two distinct contamination levels probably would be indicated. Likewise, the fluid contamination level at point 1 could and would be



SYSTEM CONTAMINATION SYMBOLS

DYNAMIC CONTAMINATION LEVEL.

Figure 2-1. Block Diagram System

modified as the fluid passed through the filter (b). Hence, the contamination level at point 2 would exhibit a different level than the fluid at point 1. Component (c) adds contaminant "EC" and "GC" to the fluid to produce the contamination level that exists at point 3. At point 3 the flow splits and the influence of the parallel components (d) and (e) is reflected by the contamination level at points 3, 4 and 5, and ultimately yields the contamination level exhibited at point 6.

The dynamic approach to contamination levels as presented above permits a true perspective of the system for the following reasons:

1. Contamination generated by a component is reflected downstream from the component.
2. Environmental conditions lead to the infiltration of contaminant through exposed areas of the components.
3. Contamination levels are reduced by the utilization of contaminant removal type components such as filters.

The contamination in the fluid which is not removed by the filtration system is known as the background level and is the lowest operating contamination level that is obtained in a system at any given time.

Rigorous contamination level equations can be written based on the block diagram for the dynamic system shown in Fig. 2-2. The equation for the contamination level at any point (n) in the system is:

$$CL_n = CL_u + EC_n + GC_n - RC_n \tag{2-1}$$

where: CL_n = contamination level at point (n) downstream from a component.

CL_u = contamination level at point (u) upstream from a component.

EC_n = environmental contaminant infiltrated through the component.

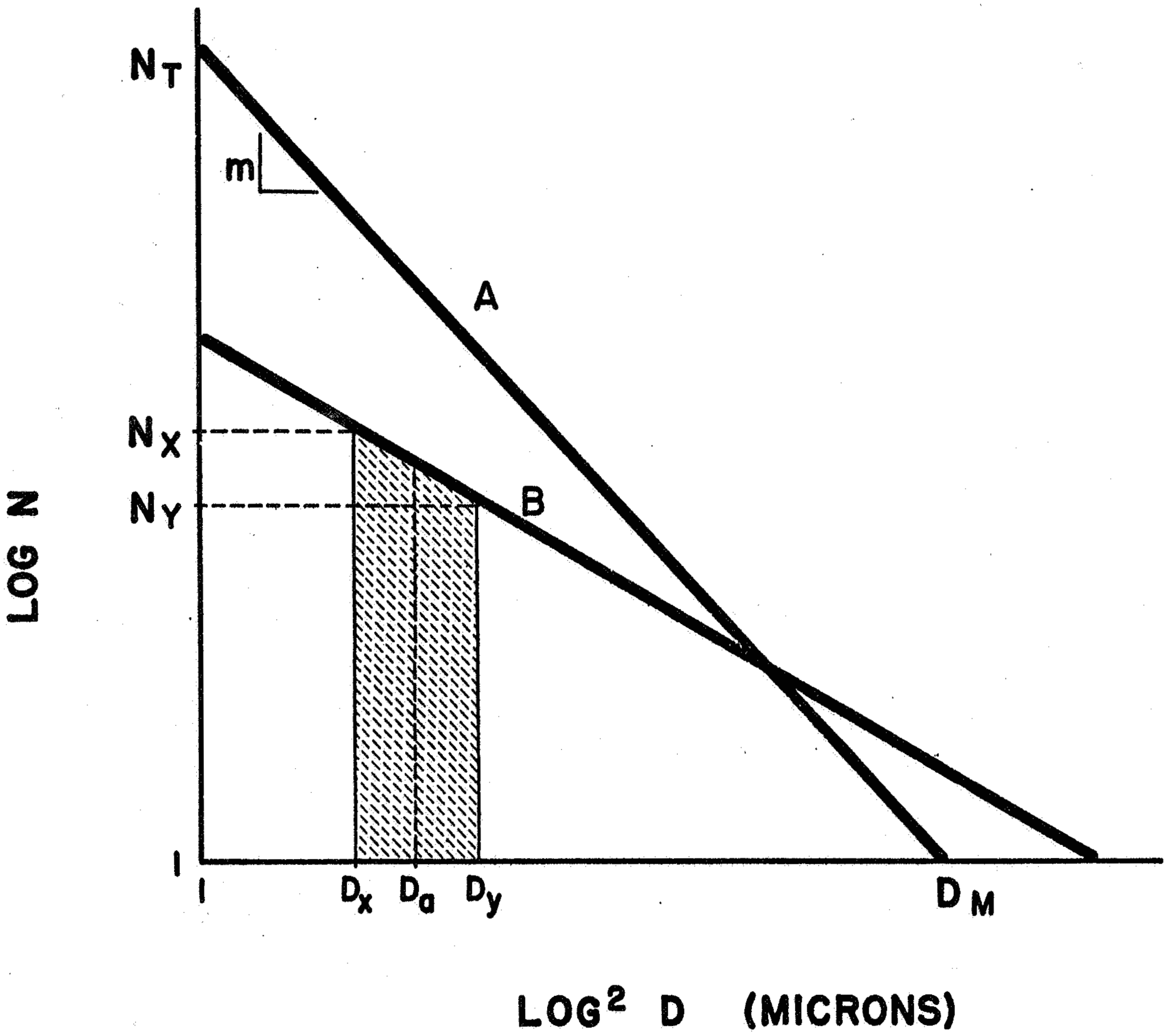


Figure 2-2. Typical Cumulative Distribution Curves.

GC_n = contaminant generated by the component.

RC_n = contaminant removed from the fluid by the component (RC_n = 0 if component is not a filter).

Equation (2-1) applies to a component of the system regardless of the type of component. For example, a component such as a pump would indicate a value of RC_n of zero; likewise, if the component is a filter, the values of EC_n and GC_n may be zero.

In the case of a system exhibiting contaminant stability or equilibrium, the filter in the system is removing contaminant as fast as material is generated or infiltrated. Such a dynamic system can be expressed by the following mathematical model:

$$RC'_n = \sum_{o}^{p} \text{"EC"} + \sum_{o}^{p} \text{"GC"} \qquad (2\text{-}2)$$

where: RC'_n = the desired contaminant removed from the fluid by the filter.

p = the number of components other than the filter.

A true representation of a system can only be obtained when a stable contamination level at the proper measuring point has been reached.

Consideration involving the dynamic system model for contamination control requires that a method must be available to express the contamination levels in a system in a concise and meaningful manner. Such a method is developed and demonstrated in the remaining sections of this chapter.

2.3 CONTAMINATION LEVELS

The gravimetric method for expressing the degree of contamination in a fluid can be mathematically justified when the particle size distribution and physical properties of the contaminant remain constant.

However, when a heterogeneous mixture of particulate matter is entrained in a fluid, gravimetric values in themselves fail to represent a useful contamination level. A gravimetric measurement for an unknown sample of fluid produces no evidence as to the size or number of particles involved. Although the gravimetric by itself may not be appropriate for describing contamination levels; when used in conjunction with the particle size distribution, meaningful levels may be expressed.

The measurement and classification of particulate matter by size distribution provide considerably more insight into the degree of contamination in fluid than is generally suspected. The particle size distribution, being the cumulative frequency of occurrence of each particle size, can approximate a statistical model which permits mathematical manipulation. Various models have been proposed to linearize cumulative particle count data and to achieve a straight line relation. The variety of models are needed because a single model cannot be used to express the particle size distribution in all fluids.

For fluid power systems, the Gaussian distribution function having a logarithmic variate has provided a good model to linearize cumulative particle count data. This model, proposed by F. W. Cole (1), uses a log-log^2 graph for plotting cumulative particle counts. The cumulative distribution curves for the contaminant entrained in hydraulic fluid extracted from aircraft, missiles, mobile equipment and machine tools have in almost every instance exhibited a straight line plot with Cole's model. Deviations from a straight line may be reasonably expected at the extreme ends of the curve. Counts of large particles may be in error because their number is often very small. Counts of small particles are susceptible to error due to limitations in the counting method.

The statistical accuracy of the particle counts for the sizes in the middle range should generally be weighed heavier in establishing a "best fit" line.

In establishing a statistical model to describe a specific distribution, the reliability of the data must be considered. Automatic particle counters usually require special calibration to agree with optical counts. In calibration studies the use of a contaminant having a known distribution is very helpful.

Assuming that a statistical model is available to linearize the cumulative particle size distribution of a contaminant, significant conclusions can be derived regarding the physical characteristics of the material. In this report, the Cole model is applied by using log-$\log^2$ paper for linearizing the cumulative particle size distribution.

2.4 CONTAMINANT CHARACTERISTICS

Important information concerning the characteristics of the contaminant can be derived by exploring the physical meaning of distribution curves. The concepts presented herein were originally introduced at the Fluid Power Research Conference at Oklahoma State University in July, 1967 (2) and later presented to the Society of Automotive Engineers (3) and the Conference on Liquid-Borne Particle Metrology (4). Consider the cumulative distribution curves (straight lines) shown on the log-$\log^2$ graph in Fig. 2-2. Any two points on the straight lines A and B are sufficient to define the lines graphically and analytically. Thus, it follows that if the number of particles greater than two arbitrary sizes are known for a given distribution, the entire plot of Log N vs. $\text{Log}^2 D$ is fixed. (The number of particles greater than 10 microns and 20 microns have proved to be convenient points in hydraulic fluid analysis.)

In reference to Fig. 2-2, Curve A exhibits a higher overall count of particles in the distribution than does Curve B. Curve A indicates a higher count of small size particles where Curve B shows more particles of the larger sizes. A statistical approximation of the total number of particles above one micron, contained in the distribution, is given by the intercept on the log N axis (point N_t for Curve A). The intercept on the $\log^2 D$ axis indicates the statistical maximum particle size (point D_m for Curve A).

A curve (straight line) on $\log\text{-}\log^2$ graph paper can be described mathematically by the equation

$$\log N = \log N_t - m \log^2 D \qquad (2\text{-}3)$$

where: $1 < D \leq D_m$

Based on Eq. (2-3), the slope of the distribution line can be expressed by the relation

$$m = \frac{\log N_t - \log N}{\log^2 D} \qquad (2\text{-}4)$$

Using Eq. (2-3), a distribution line can be defined in one of two ways:

1. by the intercept N_t and the slope m, or
2. by the intercept N_t and the number of particles greater than a diameter defined by $1 < D \leq D_m$.

In addition, Eq. (2-4) can be applied to any two points on the distribution line and the resulting slope is defined by

$$m = \frac{\log N_y - \log N_x}{\log^2 D_x - \log^2 D_y} \qquad (2\text{-}5)$$

The total volume of contaminant contained in a distribution represented by a curve defined by Eq. (2-3) is given by the relation

$$V_t = (\pi/6)\ N_t\ D_a^{\ 3} \qquad (2\text{-}6)$$

where: N_t = the total number of particles greater than one micron, and

D_a = the average diameter of all particles above one micron.

Equation (2-6) assumes that the particles in the distribution can be described as spheres.

For a finite vertical section under the distribution curve (see Fig. 2-2), the volume of contaminant can be determined by first solving Eq. (2-3) for the number of particles within the section. If the interval is sufficiently small, the arithmetic average can be used to represent the average particle diameter for the section. The total volume of contaminant for the section under the curve can be obtained by the relation

$$V = \frac{\pi}{6}\ (N_x - N_y) \left[\frac{D_x + D_y}{2}\right]^3 \qquad (2\text{-}7)$$

The total volume of contaminant in the entire distribution is therefore the sum of the volume of each section under the curve or

$$V_t = \frac{\pi}{6} \sum_{i=1}^{n} (N_i - N_{i+1}) \left[\frac{D_i + D_{i+1}}{2}\right]^3 \qquad (2\text{-}8)$$

If the size of the sections are small, the calculated volume would approach that of the true volume of the contaminant. The average volume of the individual particles is given by the relation

$$V_a = \frac{V_t}{N_t} \qquad (2\text{-}9)$$

It has been shown that a distribution described by Eq. (2-3) contains a total volume of contaminant which can be determined by Eq. (2-8). Knowing the total volume of contaminant in the distribution, the volume of the average particle can be determined by Eq. (2-9). The average particle volume is a function of the slope of the distribution curve in the same manner as the total volume of the contaminant is a function of the slope (m) and the number of particles in the distribution greater than one micron (N_t).

The slope of the distribution curve, using Eq. (2-5), can be written as

$$m = \frac{\log (N_y/N_x)}{\log^2 D_x - \log^2 D_y} \qquad (2\text{-}10)$$

Equation (2-10) states that N_y can represent the slope of the distribution curve if N_x, D_x and D_y are held constant. Using the values N_x = 10,000 microns, D_x = 10 microns, and D_y = 20 microns, the slope can be represented by simply the numerical value of N_y (the number of particles in the distribution greater than 20 microns). The graph presented in Fig. 2-3 shows a plot of the slope of the distribution curve (N_{20}) versus the associated average particle volumes (V_a) in cubic microns as determined using a digital computer.

Since the total volume of contaminant can be determined for a given particle size distribution, the weight of the contaminant (assuming an average density for the particles) can be calculated by the relation

$$W_t = V_t \rho \qquad (2\text{-}11)$$

Furthermore, since the particle size distribution is always based on a specific volume of fluid (V_f), the gravimetric level of contaminant in

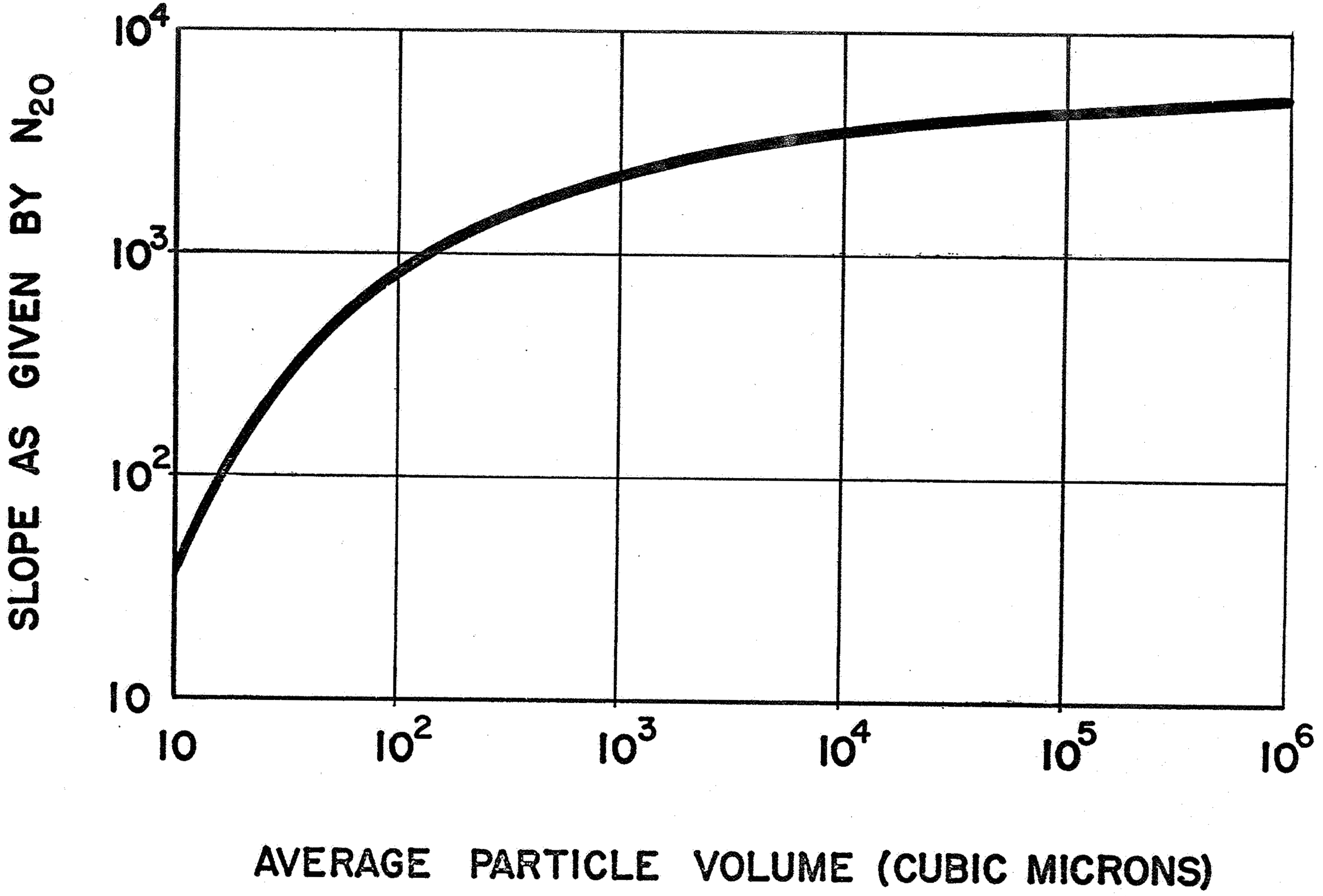


Figure 2-3. Slope of Distribution Curve Versus Average Particle Volume.

the fluid can be expressed by the relation

$$G = \frac{W_t}{V_f} \tag{2-12}$$

Thus, the particle size distribution curve for a specific volume of fluid has revealed two important aspects regarding the contamination level of the fluid:

1. the average particle volume, and
2. the gravimetric level for a specific contaminant density.

In addition, the mean or average diameters of the particles in the distribution can be calculated if and when they represent a physically meaningful characteristic of the contamination level. For example, the average volume diameter of all particles in the distribution can be determined by the relation

$$D_a = \left[\frac{6}{\pi} V_a \right]^{1/3} \tag{2-13}$$

2.5 CLEANLINESS LEVEL CHART

The characteristics of the contaminant in a fluid, as revealed by a linearized cumulative particle size distribution curve, are adequate to define the contamination level in many different applications. The Cleanliness Level was established fundamentally to define the degree of fluid cleanliness using particle size distribution data. The criterion correlates the characteristics of the contaminant by the use of one chart. The contamination level of a fluid is describable by a single numerical value. The cleanliness level number not only defines the cumulative particle size distribution curve, but it also establishes the quantity of contaminant (gravimetric level) and the average particle volume in the fluid.

The Cleanliness Level Chart shown in Fig. 2-4 permits the Cleanliness Level value for a fluid specimen to be read directly. The chart utilizes the N_{10} and N_{20} particle count (the number of particles greater than 10 and 20 microns) to define the distribution curve--represented by a point on the chart. Since a given distribution curve defines a single average contaminant volume and gravimetric level, a distribution "point" on the Cleanliness Chart is unique and physically meaningful. In other words, a distribution point defines the following:

1. A cumulative particle size distribution curve which can be drawn.
2. An average volume for all particles contained in the distribution.
3. A gravimetric level for the fluid containing the particle distribution (assuming that the specific gravity of the contaminant is known).

The constant gravimetric lines on the Cleanliness Level Chart are represented by the curved lines evenly numbered from 06 to 60. Digital computer data revealed (and it can be shown analytically) that the spacing of the gravimetric lines on the chart was logarithmic. This logical pattern suggested that cleanliness level values be assigned to reflect this characteristic. Hence, the logarithmic increments were labeled ten units apart, or specifically, gravimetric levels of 0.01, 0.1, 10, 100, 1000 and 10,000 milligrams per liter were assigned cleanliness level values of 00, 10, 20, 30, 40, 50 and 60, respectively. Although the numbering system permits ten divisions between logarithmic

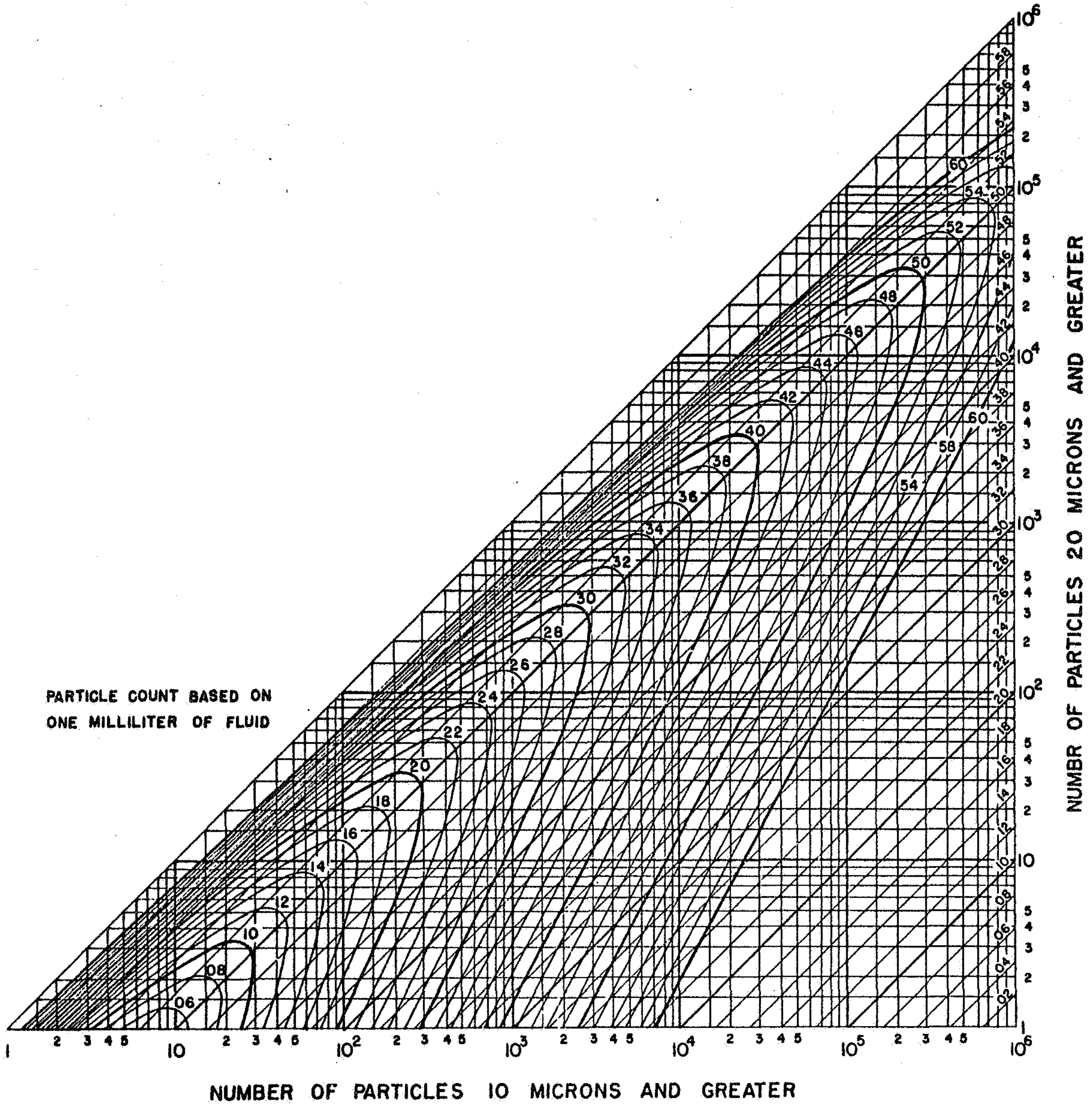


Figure 2-4. The Cleanliness Level Chart.

increments, only even numbered curves were presented on the Cleanliness Level Chart--interpolation for the specification of odd numbered cleanliness levels is recommended.

The constant average particle volume lines on the Cleanliness Level Chart are straight lines having a slope of one. Since the top of the chart represents an average particle volume which is infinite and the right hand bottom corner of the chart represents a particle volume of approximately 2.5 cubic microns (an almost imaginary condition by present day standards), the quantitiative scope of the chart is reflected. The infinite volume line was arbitrarily given a cleanliness level value of 60 on the chart to suggest large particle volumes in the same manner as 60 on the gravimetric curves indicates large contaminant quantities. Using the logarithmic increments of the chart itself, volume levels were established from 00 to 60 in even numbers. Again, interpolation to define odd numbered volume levels is recommended.

The cleanliness level of a fluid as defined by the Cleanliness Level Chart is based on the number of particles greater than 10 and 20 microns. The actual value of the cleanliness level is expressed by two-digit numbers separated by a decimal point. The number on the left side of the decimal point is the gravimetric cleanliness level value, and the number on the right side of the decimal point is the average particle volume number. As an example, a particle size distribution having 10,000 particles greater than 10 microns and 1,000 particles greater than 20 microns would define a distribution "point" on the Cleanliness Level Chart having a cleanliness level value of 35.50. The gravimetric levels and average particle volumes associated with each cleanliness level value is presented in Table 2-1. The Cleanliness Level Chart is

TABLE 2-1

INTERPRETATION OF CLEANLINESS LEVEL VALUES

LEVEL	GRAVIMETRIC	VOLUME	LEVEL	GRAVIMETRIC	VOLUME
00	0.010	2.8	30	10	6.8
01	0.013	2.8	31	13	7.2
02	0.016	2.9	32	16	7.7
03	0.020	3.0	33	20	8.2
04	0.025	3.0	34	25	8.8
05	0.032	3.0	35	32	9.4
06	0.040	3.1	36	40	10.2
07	0.050	3.2	37	50	11.1
08	0.063	3.2	38	63	12.2
09	0.080	3.3	39	80	13.5
10	0.10	3.4	40	100	15.0
11	0.13	3.4	41	130	17.0
12	0.16	3.5	42	160	19.3
13	0.20	3.6	43	200	22.3
14	0.25	3.7	44	250	26.3
15	0.32	3.8	45	320	31.5
16	0.40	3.9	46	400	38.6
17	0.50	4.0	47	500	48.8
18	0.63	4.2	48	630	64.0
19	0.80	4.3	49	800	87.6
20	1.0	4.5	50	1000	127.0
21	1.3	4.6	51	1300	200.0
22	1.6	4.8	52	1600	349.0
23	2.0	5.0	53	2000	708.0
24	2.5	5.2	54	2500	1797.0
25	3.2	5.4	55	3200	6509.0
26	4.0	5.6	56	4000	43773.0
27	5.0	5.9	57	5000	1005600.0
28	6.3	6.2	58	6300	∞
29	8.0	6.5	59	8000	∞
			60	10000	∞

based on the contaminant of unit specific gravity entrained in one milliliter of fluid.

2.6 SIGNIFICANCE OF THE CHART

Since the Cleanliness Level Chart quantitatively interprets the amount and average particle volume of the contaminant in a fluid, specific cleanliness levels can be physically established for various applications. For example, a maximum contamination level designated as 28.32 actually defines the acceptable limits of the contamination in gravimetric terms as well as by the particle size distribution. Such limits for contamination levels have practical significance because of the following:

1. System components have been shown to exhibit a contaminant sensitivity or a tolerance which can be described in terms of contaminant quantity and particle size distribution.
2. Contamination control by filtration involves maintaining fluid cleanliness levels within specified gravimetric and particle size limits.
3. Contaminant generation within a system is recognized by changes in the gravimetric level and/or particle size distribution.

Based upon the analysis and correlation of hundreds of fluid samples, it is recognized that various sections of the Cleanliness Level Chart are applicable to specific types of systems. For example, contamination levels of concern to NASA generally fall below a gravimetric cleanliness value of 22.

2.7 MEASUREMENT OF CONTAMINATION LEVEL

The measurement of the contamination level in a fluid system must be a highly coordinated activity. In order for a particle size distribution to be meaningful, the actual fluid sample must be truly representative of the system fluid. This means that the sample container must be "clean," the sample valve appendage does not slough particles, and the extraction technique produces a sample exhibiting the same distribution as exists in the actual system. Dependable methods have been developed to permit the collection and evaluation of fluid samples and these methods will be reviewed.

The cleaning of fluid sample containers is prerequisite to achieving a representative sample from a system. There have been many erroneous decisions made based on the contamination level of fluids collected in "dirty" bottles. A rigid procedure has been developed at OSU in the course of the NASA filtration studies which has yielded excellent results. This procedure is presented in Appendix B.

The extraction of a fluid sample exhibiting a contamination distribution equivalent to that of the fluid in the system has been a phase of previous NASA contracts at OSU. The technique developed has been an important part in achieving the specific objectives of the current contract. In order to avoid confusion among the recipients of this report, a full explanation is given in Appendix C of the sampling technique used for this work.

The method used to obtain the particle size distribution of a fluid sample utilizes an automatic particle counter which was specially calibrated to agree with optical count data. The details of the method are explained in Appendix D. A detailed account of the gravimetric method used in verifying the results under this contract is presented in Appendix E.

2.8 EXPERIMENTAL VERIFICATION

In an attempt to develop procedures for the correlation of filtration performance relative to the needs of fluid power components a non-generating hydraulic system was fabricated. The system was designed using components which minimized the entrance of the three major types of contamination: (1) environmental contaminant, (2) generated contaminant, and (3) built-in contaminant. A low pressure stainless steel centrifugal pump was utilized together with stainless steel tubing and a clear plastic reservoir. All valving was of the ball type to reduce silting areas. The sample valve was left in the open position at all times, with a length of tygon tubing conducting the sample valve fluid to the reservoir when samples were not being extracted.

After a number of modifications and intervening tests, the stand exhibited a non-generating characteristic. This meant that the system would maintain the same particle size distribution over a four-hour circulation period. The capabilities of such a stand were needed to meet the requirements of the following types of tests:

1. Contamination level trajectories resulting from increasing the quantity of a specific contaminating material.
2. Correlating active system contamination levels with cleanroom bench type tests.
3. Contamination level trajectories resulting from a specific filter in the system. The appraisal of filtration performance by this method will be discussed in Chapter III.
4. Evaluating the effect of various contamination levels on spool valve performance. The results of this work will be discussed in Chapter IV.

The results of the contaminant level tests using the non-generating test stand are presented with the aid of the Cleanliness Level Chart. In Test No. 1 above a series of injections of AC Fine Test Dust were made in the stand, fluid circulated for approximately 30 minutes and samples extracted. The results of a typical series of injections are graphically displayed in Fig. 2-5. It can be noticed that the trajectory initiated at a volume level line of 52 and became tangent to a volume level of 51 as contaminant was injected. The figure shows that the particle size distribution exhibited by AC Fine in this system indicates an average particle volume of 200 cubic microns according to Table 2-1. Gravimetric levels obtained from cleanroom tests correlated perfectly with the uncorrected gravimetric values indicated by the chart. This revelation substantiates current shape factor studies by Fred Cole at the Bendix Filter Division on AC Fine Test Dust. The shape factor of the contaminant appears to offset the density factor of approximately 2.5.

Numerous cleanroom tests have been performed on particle size distributions of AC Fine Test Dust. Conclusive cleanroom results (static test) indicate that the contaminant has a volume level of 52.5. These results do not agree with the distributions obtained from the non-generating stand which produced a level of 51. One answer that can be advanced at this time is that there is a difference between static and dynamic tests. Notice a steady state is reached where the trajectory becomes tangent to the 51 volume line. Future tests should more fully explain the discrepancy in results.

2.9 CONCLUSIONS AND RECOMMENDATIONS

The development and utilization of the Cleanliness Level Chart has revealed new insight into the problems of contamination levels. The chart quantitatively depicts the influence of system variables on the contamination level. For the first time it appears conclusively that a proper evaluation of contamination levels can be offered.

The major task remaining at this time is gaining additional experience as to the meaning of various changes in contamination level which

OSU LEVEL	GRAVIMETRIC	VOLUME
00	0.010	2.8
02	0.016	2.9
04	0.025	3.0
06	0.040	3.1
08	0.063	3.2
10	0.10	3.4
12	0.16	3.5
14	0.25	3.7
16	0.40	3.9
18	0.63	4.2
20	1.0	4.5
22	1.6	4.8
24	2.5	5.2
26	4.0	5.6
28	6.3	6.2
30	10	6.8
32	16	7.7
34	25	8.8
36	40	10.2
38	63	12.2
40	100	15.0
42	160	19.3
44	250	26.3
46	400	38.6
48	630	64.0
50	1000	127.0
52	1600	349.0
54	2500	1797.0
56	4000	43773.0
58	6300	∞--
60	10000	∞

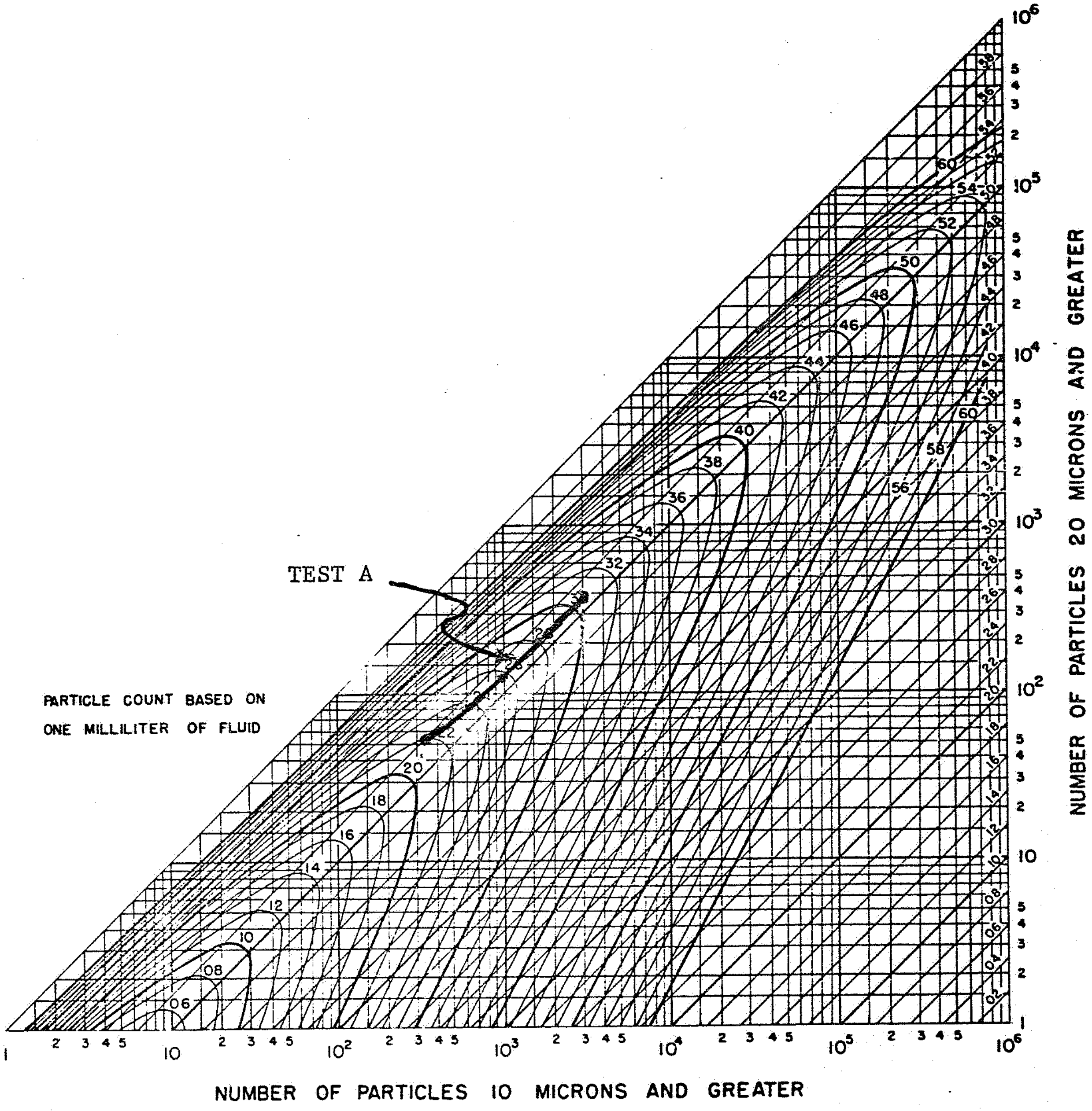


Figure 2-5. Gravimetric Trajectory.

can appear on the chart. For example, recent tests have shown that wire cloth may allow increases in the gravimetric level while decreasing the average particle size. In some cases of depth media, however, gravimetric level decreased while the average particle size increased. If future work verifies the conditions conclusive to these results, a new method has been discovered in specifying the type filtration needed to achieve a specific contamination level.

CHAPTER III

FILTRATION MECHANICS

3.1 INTRODUCTION

Mechanical media, which are used for filtering contaminating particles from dynamic fluid streams, are descriptively categorized as either surface or depth materials. The basic question is, what are their differences? And secondly, if there are differences, when is one medium type preferred over the other in terms of functional requirements?

The answer to the first question is obvious. Strictly speaking, a medium is of the surface or depth category depending on where the contaminating particles are retained with respect to the medium in question. When a medium retains particles in its depths, it is acting as a depth medium. When particles come to rest on the surface of a medium, then it is a surface medium. This is to say, a medium may act in either or both categories, even simultaneously, depending on the relative properties of the medium and the contamination particles. Conclusively, the difference between the two is strictly functional.

Structural differences come into meaningful play only when a size range is specified for the contamination population which is to be subjected to the filtering action. In the cases of aerospace hydraulic and fuel systems, the contamination population have been generally described. There, wire cloth is a prime example of the surface media category; and randomly oriented fiber matrices are identified in the depth media category.

By the way of a general characterization, the flow passages of surface media are simple just as their filtration mechanism is relatively uncomplicated. They offer a veritable barrier to all solid particles larger than the pore openings and a gate to many of the smaller particles. Excellent manufacturing control and superior structural reliability are generally attributed to the wire cloth variety of surface media. Surface media can produce a sharp wire classification in the effluent, but their contamination capacity is low by some standards.

Depth media exhibit flow passages which are more complex and relatively long. The filtration mechanism is also complex. Besides offering a barrier to larger particles at its surface, a depth filter offers absorbent traps to the smaller particles that find their way into the interstices of the media. They achieve separation of contamination which includes the small particle size range which may go unchallenged by surface media. Manufacturing control is not as precise as with most surface media. And the hazard of media migration tends to be more prominent. As a final mention, the contamination capacity of depth media appears to be high.

Both surface media and depth media have their limitations and attributes. Singularly, applications can be found where one type or the other works "best". Based on laboratory examination, when used together the media combination may be capable of producing filtration of unequaled quality.

It follows that the second question is much more difficult to resolve. There are always many pertinent engineering aspects which must be carefully weighed relative to specific applications. Such as: initial cost, maintenance cost, structural reliability, size and weight limitations, contamination capacity, built-in contamination, separation efficiency, and contamination retention reliability, to mention a few. However, the research conducted at Oklahoma State University in the filtration area is oriented mainly towards the study of the basic nature of filtration. The premise is that filtration theory can be established whereby a scientific basis for the specification and design of filtration systems will be secured ultimately.

3.2 DEPTH MEDIA FILTRATION

Fluid transmission and contamination retention are the two fundamental functions of hydraulic filters. The opposing nature of these two functions establishes the basic goals for filtration research. Considering only the fundamental functions of filter media, it is easy to define the perfect contamination filter for fluids. This would be the filter that offers zero resistance to flow and an infinite resistance to the transmission of contamination particles. In a realistic sense, the basic goals for research in filtration must be to determine a quantitative description of filtration parameters whereby the inter-relationships of flow, pressure and other filtration characteristics are comprehensively expressed.

The important parameters of surface media filtration have been delineated by means of the research conducted in the past phases of this project. Design criterion in terms of media properties have been set forth for use by the industry. The referenced research has continued into the area of depth media filtration. Specific interest has been directed to depth media of the randomly oriented fiber construction.

As it has been stated previously, the work is generally concerned with the expansion of filtration theory which will produce a scientific basis for the specification and design of mechanical filtration systems. With depth media playing an increasing role in contamination control for hydraulic systems, the need for such study is urgent, and the expectations for achieving the ultimate goal are clearly more attainable.

It has been reported in earlier phases of this research effort that a high degree of agreement is exhibited when the mean pore size of the normal distribution associated with a good quality wire cloth medium is determined by mercury intrusion and filtration efficiency techniques. It has also been demonstrated that the mean pore size, determined by the filtration efficiency method, can be used in the formulation of an excellent mathematical flow and filtration model applicable to wire cloth medium. Philosophically, the success that has been enjoyed means that the fluid "saw" the passages through the wire cloth the same as did the solid particles. This is certainly not the case when depth media are subjected to the same testing methods. Past attempts to mathematically model a depth medium using methods applicable for wire cloth show a marked discrepancy with experimental results. Observations made during the referenced research phase indicate that a mechanism similar to cake filtration is more applicable to depth media filtration than is the complete blocking mechanism which applies to wire cloth. However, the applicability of cake mode and non-applicability of the blocking mode are exhibited in degrees that are influenced by parametric values. Of course, the two cases are actually the end points of the filtration spectrum. Material in the following section is quite revealing in reference to the preceeding statement.

Research with surface and depth media has revealed that the media parameters that effect fluid transmission and contamination retention are not always identical. This simple fact proves to be very significant to the results of the current work. For example, consider the following equation which applies for laminar flow of fluid through filter media:

$$Q = \frac{\Phi A D^2}{32 \mu \tau L} P \qquad (3\text{-}1)$$

where: Q is the total flow through a medium having an area, A

P is the pressure differential across the medium

Φ is the porosity of the medium

D is some effective diameter of the pores

L is the shortest possible flow path through the medium

τ is the effective tortuosity of the flow paths

μ is the dynamic viscosity of the fluid.

Note that all of the flow affecting parameters shown in Eq. (3-1) are also contamination retention parameters. The only functional differences are the facts that in respect to the fluid, transmission is allowed and in respect to the contamination particles, transmission may be denied. Hence, the idea of the opposing nature of transmission and retention is presented in an analytical sense.

3.3 EXPERIMENTAL ACTIVITIES

Before Eq. (3-1) can be used for the specification and design of filters, the media parameters must be measurable quantities. And in a rigorous analytical sense, the variations of the parameters, due to the presence of filtration, require the general expression to be a differential equation. Equation (3-1) then is a steady state solution to the differential equation of filtration.

Except in special cases, none of the techniques employed in measuring D for wire cloth have proved successful with depth media. Repeated attempts in testing and correlation of the resulting data have been futile in the successful result domain. The following discussions summarize the testing and their respective results.

1. Bubble and Boiling Tests - Since the bubbles created by forcing air through submerged media specimens, in accordance with the property of relative surface tension, are formed at the surface of the media, the measurement is pertinent only to the surface openings of the material. The non-uniformity in openings at the surface of many randomly oriented fiber beds reduces the information gained from these tests to an almost meaningless number. Some conclusions from the tests can be gained, but these conclusions should be tempered with extremely cautious analysis. Two useful applications for bubble testing depth media are for qualitative analysis of the effectiveness of seals at the seams and end caps of filter elements, and for establishing a general idea of the nature of the pore size distribution which characterizes the medium in question. For the true depth matrix, relative to the contamination found in ordinary hydraulic systems, it appears that a so-called boiling point is not generally distinguishable.
2. Mercury Intrusion Testing - The usefulness of data which was generated by the test procedure conducted for determining pore sizes remains in doubt. It appears that the void spaces are

much too large and irregular, in relation to the control dimensions of the medium, to achieve sufficient sensitivity in the measurements. However, mercury intrusion is an excellent technique for determining the porosity of depth media.

3. Filtration Efficiency Testing - This technique was utilized to determine information relative to the pore size distribution of the depth materials that have been tested. In most cases, the tests indicate a log normal cumulative distribution as one may expect for randomly oriented fiber matrices.
4. Effective Filtration Diameter Tests - The results of this test were inconclusive for determining D_e. Since the efficiencies of the media specimens were relatively high at low micron sizes, the sensitivity of this test may be too low for precise application to the case.

Additional conclusions from the tests mentioned above can be listed as follows:

1. The techniques used to measure filter media parameters in the case of wire cloth media will not in general serve with sufficient utility for measuring depth media parameters. Certainly, the basic filtration mechanisms for depth and surface media differ greatly. Surface filters function as a two dimensional seive where depth media are more absorptive in nature.
2. It appears that the main filter parameters that contribute to particulate matter retention in a randomly oriented fiber matrix, on a steady state basis, are porosity (ϵ), depth (L), tortuosity (τ) and the effective dimension (D). These

individual parameters are not independent of each other, or of the contamination parameters which are implicit in the equation.

3. The mechanism of depth media filtration appears to be very similar to the cake filtration phenomena that has been suggested by Hermans and Bredee. Optical examination reveals that contamination particles (such as A.C. Fine Test Dust) that are retained in a fiber matrix become more or less absorbed within the structure of the medium. More than one particle becomes trapped in individual void spaces. That is, the particles build up a sort of cake within the labyrinth of the media. The extent of the similarity is not clear for the general case at this time.

Efficiency Tests

Considering the results and conclusions listed above, a new experimental approach was deemed necessary in the interest of achieving insight to the effects of the pertinent depth filtration parameters. A testing procedure was devised which appeared capable of revealing the nature of some of the apparent effects that had been indicated by the earlier experimental effort.

The crux of the established procedure is to determine the filtration efficiency of fiber type depth media in terms of all of the media parameters that are known to effect filtration efficiencies. A subsequent test is conducted to measure the flow space of the medium. Theoretically, the flow space measurement, corrected by the related filtration efficiency, should generate a number which is proportional to the contaminant holding capacity of the material.

A useful form of the applicable laminar flow relationship for filter media is given by:

$$Q = \frac{\Phi^2 A^2}{8\pi\mu\tau LN} P. \qquad (3\text{-}2)$$

Lumping the nebulous parameters together, results in the following equation:

$$Q = \frac{K_o \Phi^2 A^2}{\tau L} P. \qquad (3\text{-}3)$$

It follows that the factor $\frac{K_o \Phi^2 A^2}{\tau L}$ is simply the slope of the experimentally generated flow pressure curve for a medium.

Another laminar flow equation which relates gas flow through a porous medium with the pertinent parameters is

$$W = K_1 \frac{D^4}{L} (P_1{}^2 - P_2{}^2) \qquad (3\text{-}4)$$

where: W = mass flow rate
P_1 = upstream pressure
P_2 = downstream pressure
D = characteristic flow dimension
L = distance through medium
K_1 = constant determined from fixed medium and steady state gas properties.

Provisions are not made for the effects of a tortuous flow path in Eq. (3-4). It is assumed that the losses due to tortuosity of the gas flow path are negligible.

By setting a flow rate to produce a specific pressure drop, Eq. (3-4) is reduced to

$$\frac{D^4}{L} = WK_2. \qquad (3\text{-}5)$$

Multiplying Eq. (3-5) by the slope factor of Eq. (3-3) and inverting gives

$$\frac{L^2}{\Phi^2 D^4} = \frac{K_5}{W} \qquad (3\text{-}6)$$

where K_5/W can be determined experimentally for the given fluid media.

Equation (3-6) contains all the unknowns that are usually difficult to measure in a depth medium. Also, the variables are in the proper arrangement for a possible correlation through proportionality with filtration efficiency. The factor on the left is referred to hereafter in this report as the "Filtration Efficiency Constant, Z."

Filtration efficiency tests on a gravimetric basis using injections of A. C. Fine Test Dust in MIL-5606 hydraulic fluid, have been conducted. Figure 3-1 shows a straight line correlation representing the trend of the data from the efficiency tests with variations of Z. All data points deviate from the line by less than ten percent. The line is considered to be a reasonable experimental correlation for contamination data of this type. Subsequent tests are now being conducted on a greater variety of the fiber type medium in the interest of gaining additional statistical inference to the trend.

Contaminant Capacity Tests

Because of the nature of contaminant entrapment that occurs in the fiber matrix, it is theorized that a depth medium's specific contaminant capacity is related to the space within the medium that is available to the flow of fluid. The specific contaminant capacity of a filtering medium is defined here as the amount of contaminant (by weight)

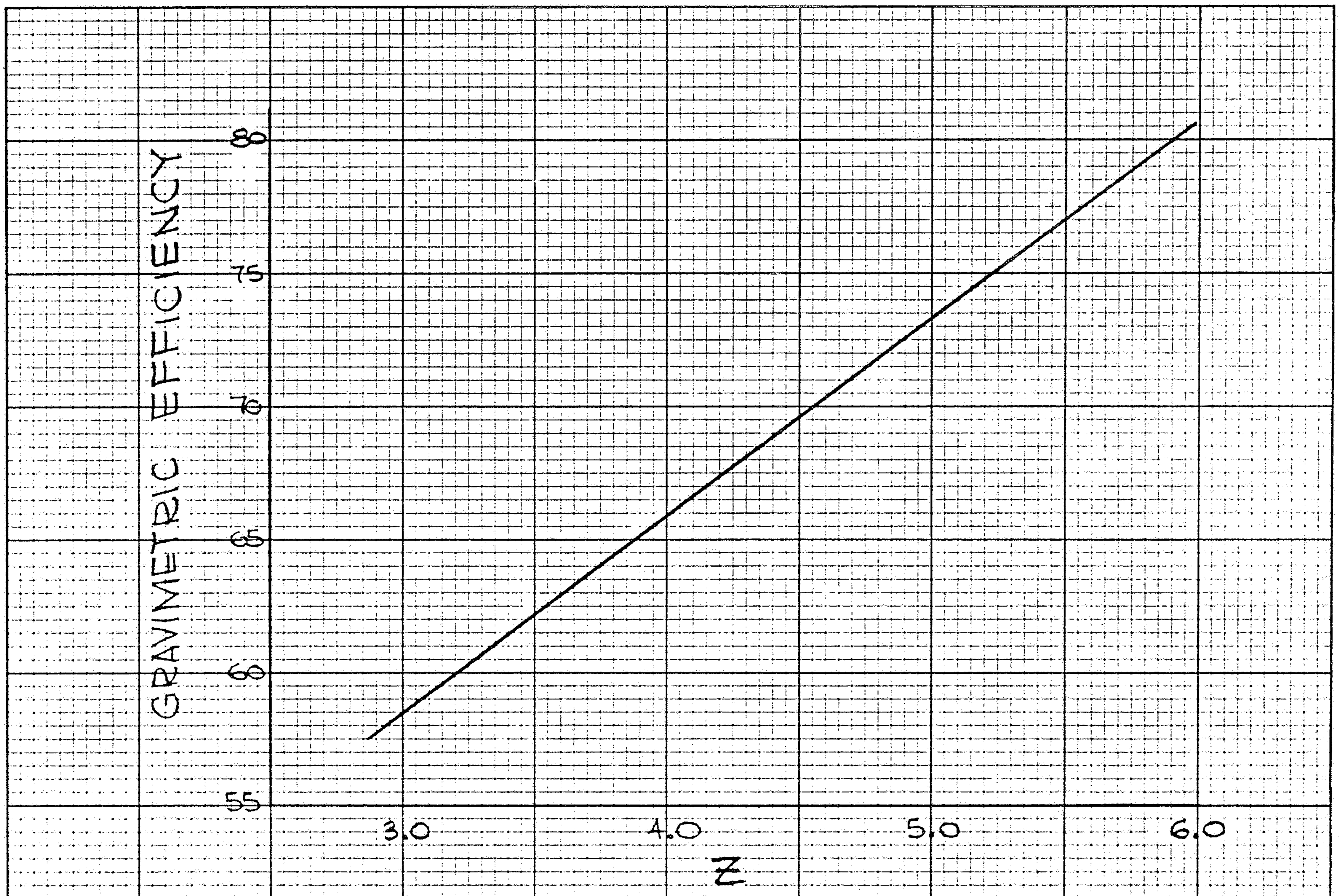


FIGURE 3-1. STRAIGHT LINE CORRELATION REPRESENTING THE TREND OF THE DATA FROM GRAVIMETRIC EFF. TESTS WITH VARIATIONS OF Z.

that is required to "plug" the medium. A medium is said to be "plugged" when the pressure drop increases to an arbitrarily specified limit.

Taking Eq. (3-4) which relates the mass flow of air through a porous medium under steady state conditions, and combining constants, gives

$$W = \frac{C_1 A_o^2}{L} \qquad (3\text{-}7)$$

where: A_o is said to be a value representing the total area of the flow paths

L is the length of the flow path

C_1 is a constant of proportionality calculated with a fixed pressure setting and constant fluid properties.

In order to evaluate the value of A_o in Eq. (3-7), with contaminant capacity, experimental tests were performed. The contaminant capacity tests were conducted on various media specimens using A.C. Fine Test Dust injected into MIL-5606 hydraulic fluid. The apparent contaminant capacity was taken as the amount (weight) of the injected contaminant that corresponds to a pressure drop of 10 psi across the medium. Figure 3-2 shows a typical loading curve for the depth media tested. Of course, the weight of the injected contaminant includes the weight of the contaminant that is transmitted through the medium as well as the contaminant retained by the medium. Hence, the term "apparent contaminant capacity" is meaningfully applied. The value is corrected to the "true contaminant capacity" when it is multiplied by the separation efficiency that had been determined previously for the medium. This was done by using correlated efficiency values taken from the curve shown in Fig. 3-1.

Figure 3-3 is an example of so called true contaminant capacity data plotted against the hypothetical parameter, A_o. As in the

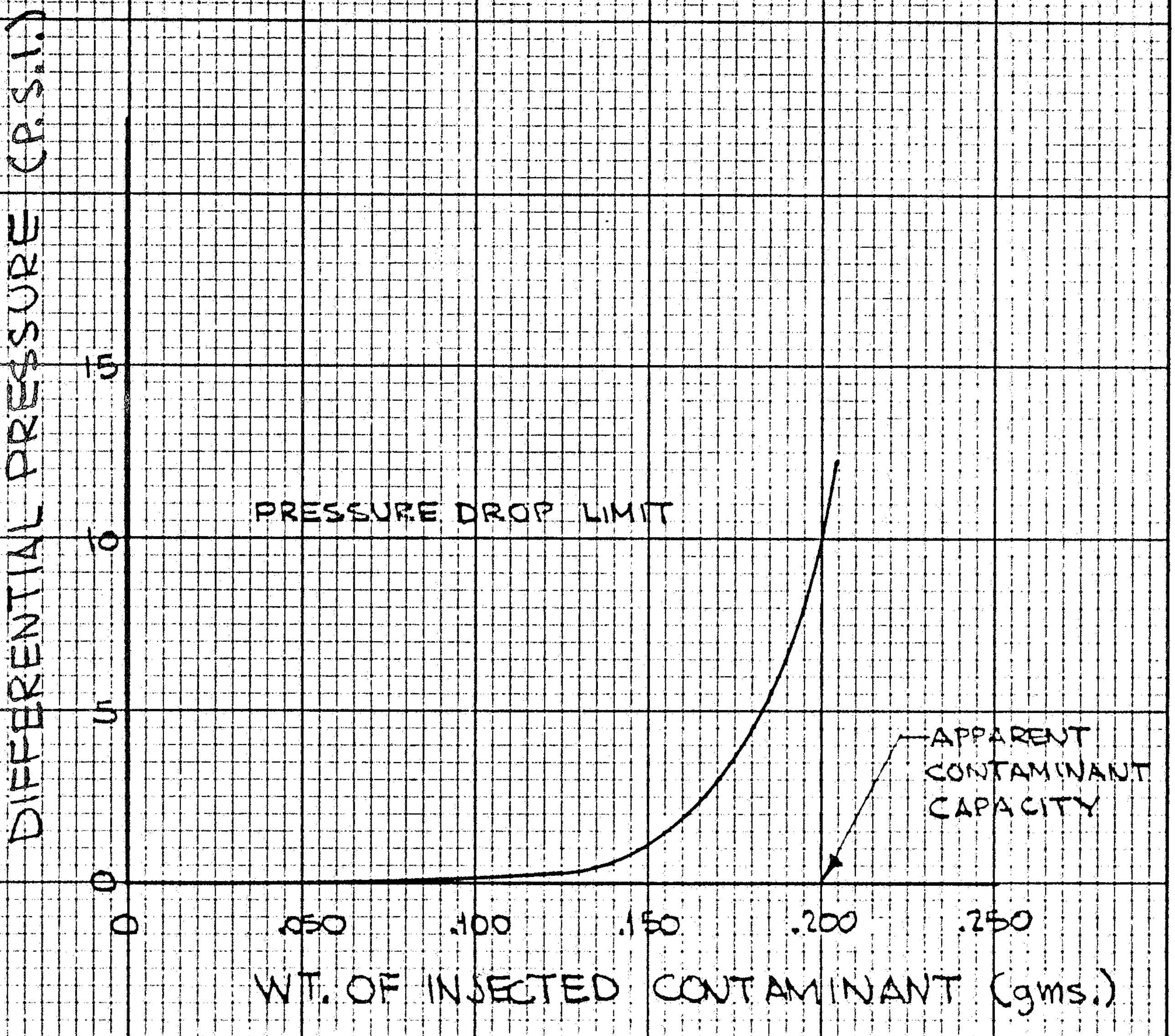


FIGURE 3-2, TYPICAL LOADING CURVE FOR THE DEPTH MEDIA TESTED.

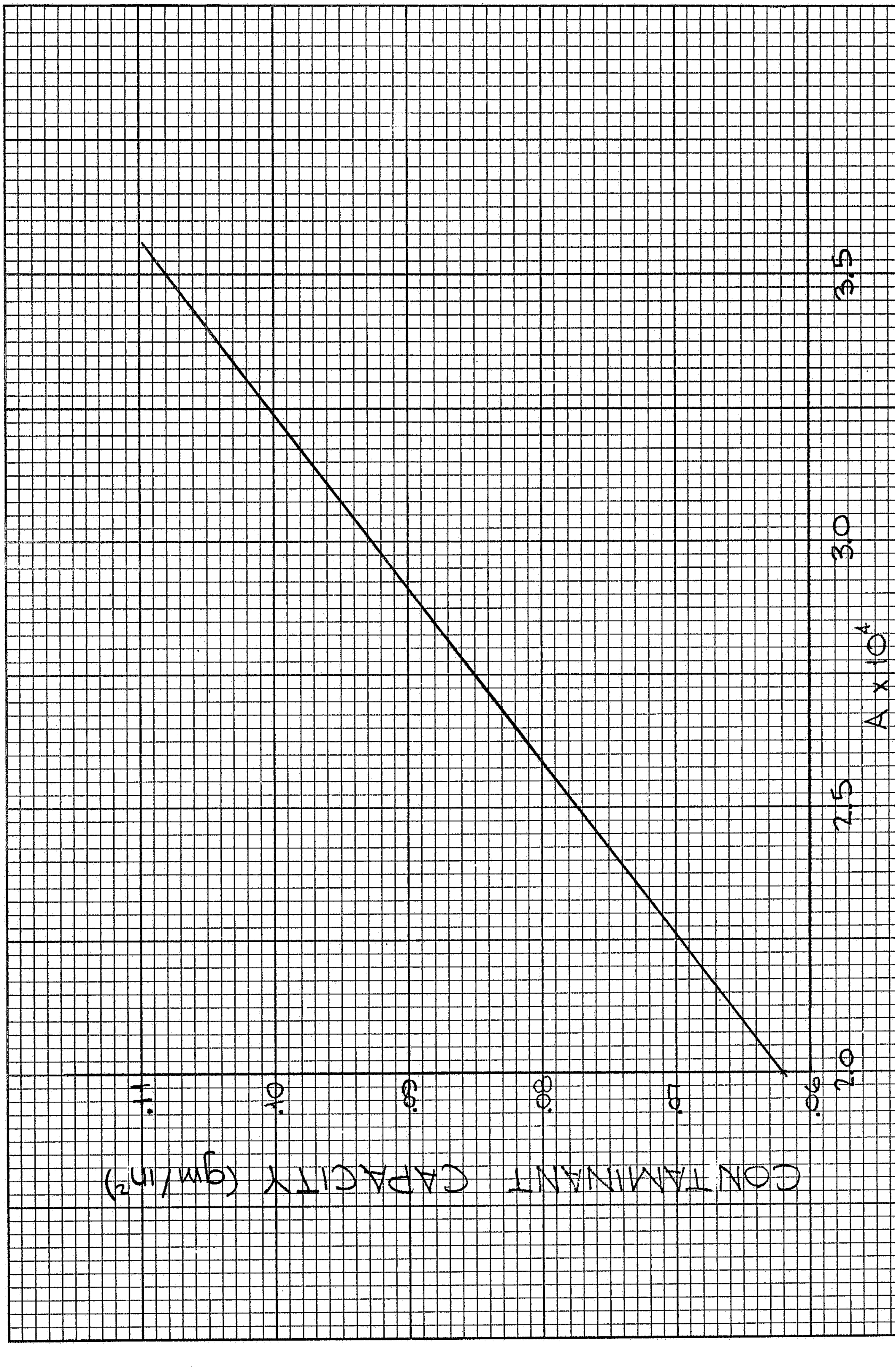


FIGURE 3-3, TRUE CONTAMINANT CAPACITY DATA PLOTTED AGAINST THE HYPOTHETICAL PARAMETER A.

illustration of the efficiency data correlation, the straight line was drawn arbitrarily to represent the discernible trend of the data. The quality of even this crude experimental correlation is good by most standards in the subject area of research.

3.4 EXPERIMENTAL RESULTS OF FILTRATION RESEARCH USING CLEANLINESS LEVEL CONCEPTS

Chapter II discussed the concept of cleanliness level representation and measurement as it is being applied in general through the research work of this project. Fundamentally, the concept of cleanliness level representation will probably mean as much to contamination control and fluid power system design as any other single contribution to modern fluid power technology.

The work on this project, applying the concept to filtration, is typically illustrative to the above claim. The information that is reported herein will show the results of simply applying the basic measuring technique to describe cases of filtering action.

Briefly, the procedure involved use of the low contamination generating stand which was described in Chapter II. A cleanliness level was artificially established in the circulating fluid of the stand by adding an amount of A.C. Fine Test Dust. After the cleanliness level of the fluid was identified, the contaminated fluid was then systematically subjected to the filtering action of flat specimens of a depth media and wire cloth, in that order. Samples of the circulating fluid were taken for analysis of the filtering action at discrete times.

Figure 3-4 graphically illustrates the typical particle count results obtained from the tests. The cumulative particle counts, as determined by using a HIAC particle counter (calibrated to a standard

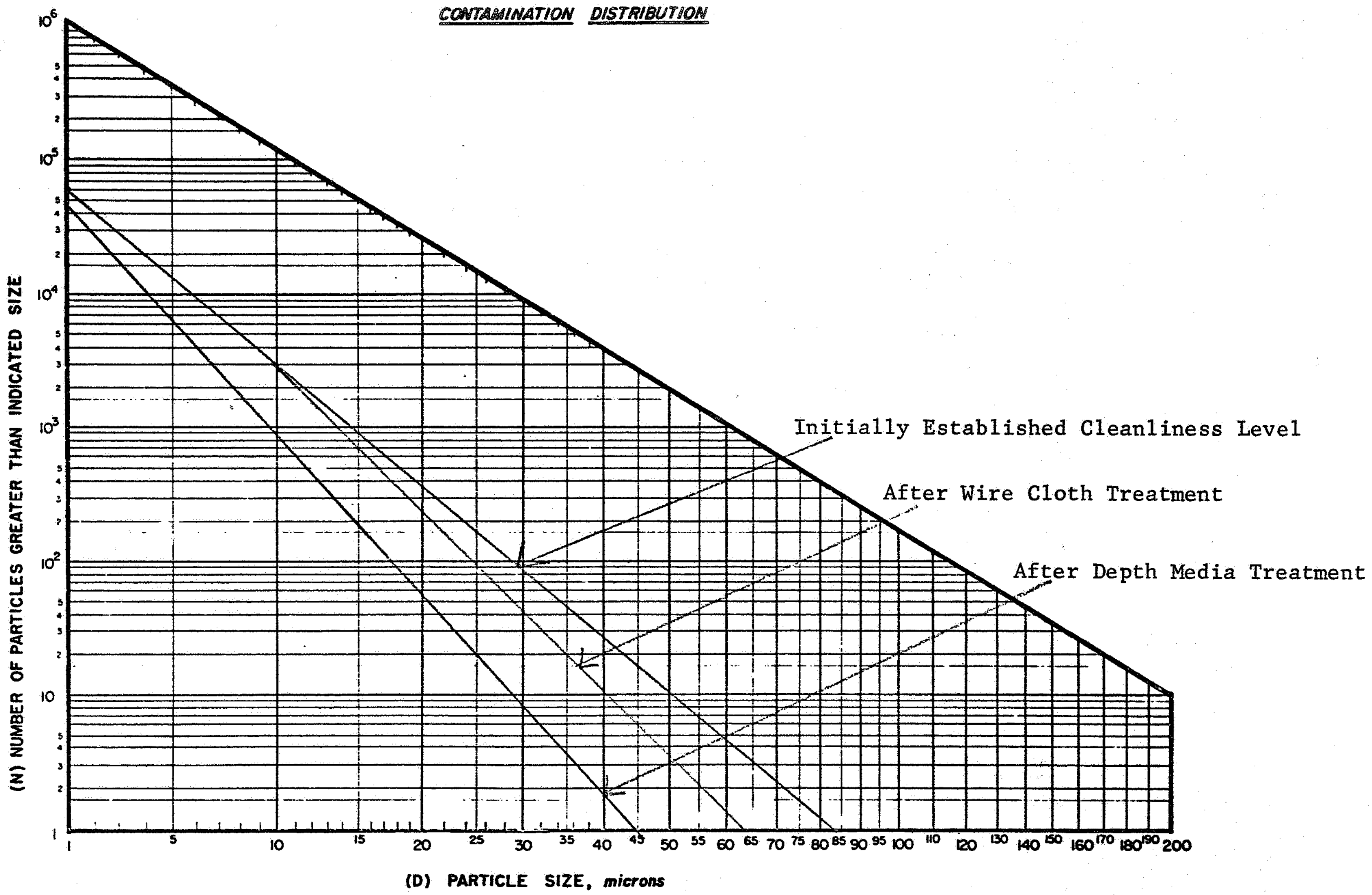


Figure 3-4. Typical Particle Count Results Obtained from Cleanliness Level Filter Media Tests.

determined at OSU) are listed in Table 3-1. This table is for a wire cloth specimen (165-1400 Dutch Twill Weave). Table 3-2 is a compilation of similar data from tests conducted on a nominal 10 micron, randomly oriented fiber medium.

The upper most straight line of Fig. 3-4 represents the cumulative contaminant particle size distribution as was initially established in the non-generating system. Notice that the distribution of the test dust is of the log-$\log^2$ variety. The variety is similar to that which has been found through the analysis of many samples from operational fluid power systems. That is, fluid power systems operating in conjunction with airborne, stationary, earth moving, indoor and outdoor equipment.

The other straight line which is referenced to the affecting randomly oriented fiber filtering medium represents a change in particle distribution as well as a weight quantity change. The line is steeper, showing a decrease in the average particle size. And, the reduction in counts of all sizes present represents a weight quantity removal. Another interesting note to the shift of the line comes to light by realizing that the randomly oriented fiber medium that was used also exhibits a log-$\log^2$ distribution in its effective filtering pore sizes.

The composite of straight lines which is referenced to the affecting wire cloth medium, illustates an interesting point. Although the knee of the composite is shown to occur exactly at the 10 micron size, the accuracy of that size has not been determined at this time. The point is nevertheless, there is a definite knee, which is theorized to be associated with the well defined performance nature of similar wire cloth materials. The composite line illustrates a performance type that

TABLE 3-1

WIRE CLOTH 165-1400 MESH

Fluid Sample Number	Number of Particles of a Discrete Size and Greater			
	10	20	30	40
1	3048	208	60	11
2	3009	178	46	9
3	2805	156	31	7
4	2850	128	27	2
5	2140	87	22	7
6	2178	50	18	6
7	2501	54	17	7
8	2070	35	12	4
9	1950	29	10	3
10	2086	21	5	2
11	1712	12	3	1

TABLE 3-2

DEPTH MEDIA SPECIMEN

Fluid Sample Number	Number of Particles of a Discrete Size and Greater			
	10	20	30	40
1	877	29	13	3
2	1432	27	9	5
3	1013	16	6	1
4	709	32	12	5
5	702	21	8	2
6	922	14	5	2
7	682	39	4	4

can be correctly associated with the effect resulting from filtering a $\log$-$\log^2$ contaminant population through a normal pore size distribution.

Obviously, the implications of these typical results are as promising as they are interesting. In light of securing theory for the support of general system and specific application design, a way to proceed with supporting research is clear.

3.5 SUMMARY

Specific conclusions based on discrete tests were presented in the preceeding sections of this chapter. However, it is premature to articulate general conclusions based on the work done up to the time of this writing. More tests and analyses are required, and are being conducted, for the purpose of supporting general conclusions on the performance of depth media filters.

A basic difference in the performance of wire cloth filters and depth media filters is indicated by the particle size distribution data used in a comparison of performance of a wire cloth and a depth medium filter. Of course, one would reasonably expect a difference in the separation performance of a medium with a normal pore size distribution (wire cloth) and a medium with a $\log$-$\log^2$ distribution (randomly oriented fiber depth media). What is important about the existing performance differences is that flexibility of media selection for specific application requirements is enhanced. Thinking in terms of controlling the size distribution as well as the quantity of contamination, where the two in combination constitute a defined contamination level, it becomes apparent that the proper selection of a filtering medium or media is critical. Experience bears out that filtering medium selection must be made with full cognizance of the contamination situation in terms of contaminant parameters and component sensitivity to the existing contamination. It follows that contamination levels, contamination sensitivity, and capabilities for contamination control should all be measured in the same contamination level terms. In this way, allowable contamination standards with scientific bases, can be set and properly maintained.

CHAPTER IV

CONTAMINATION TOLERANCE LEVEL

4.1 INTRODUCTION

The contamination tolerance level of a component in a system must be defined as the maximum contamination level of the fluid being subjected to the component, which will not affect the performance, reliability or life of the component. In other words, a component that is not sensitive to the level of contaminants in the fluid does not "realize" the presence of the extraneous material and therefore, as far as the component is concerned, the contamination does not exist.

The individual operating elements, comprising a system component, impose explicit limitations upon the contamination level of the fluid because of the nature of the fabrication material, component design configuration, operating conditions, and fluid properties. These limitations on the contamination level establish the contamination tolerance level for the component, and the tolerance for a system of components is established by the contaminant tolerance level of the greatest contaminant sensitive component included in the system.

The importance of having a mathematically rigorous method for expressing the contamination level of the fluid in a system should be recognized. Obviously, without such a method a specification for the contamination tolerance level of a component would be undefinable and at best would reflect a qualitative condition. The Cleanliness Level

Chart developed and presented in Chapter II has provided an effective method to specify and display tolerance levels. This method permits a tolerance level to be established utilizing procedures commonly used in the cleanroom to evaluate fluid samples. Knowing the contamination level of the fluid being subjected to a given component, permits the appraisal of various contamination levels on the performance of the component.

4.2 FACTORS AFFECTING TOLERANCE LEVELS

The factors affecting the contamination tolerance level of a component in a system are related directly to the configuration of the component, the fabrication materials, the operating conditions, and the properties of the fluid used in the system. A list of these factors would include the following:

1. Component Configuration Factors
    a. element design
    b. clearances
    c. surface finish
    d. surface hardness
    e. heat dissipation from critical areas
2. Component Material Factors
    a. seals - elastomers
    b. bearings
    c. housings and sleeves
    d. moving parts
3. Operational Factors
    a. operating speed
    b. operating pressure

   c. operating temperature
   d. actuating force
   e. environmental envelope

4. Fluid Property Factors
   a. fluid viscosity
   b. film strength - boundary layer thickness
   c. surface tension

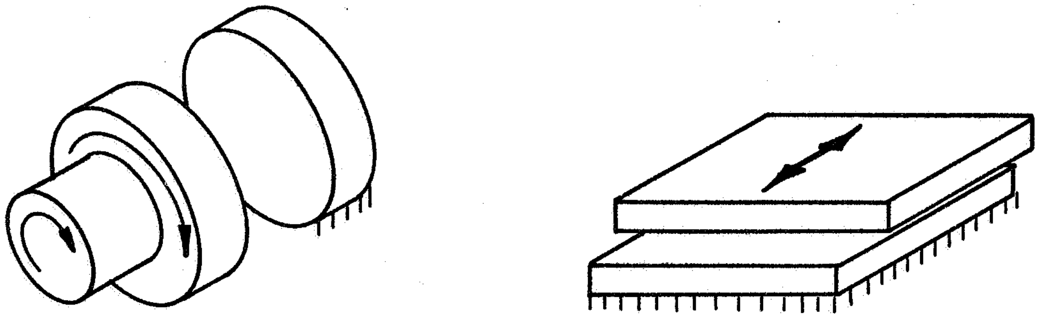
The components used in a fluid system utilize a combination of several basic mechanisms of elements. The manner in which these mechanisms are used within a component establishes not only the contaminant tolerance of the component but also the contaminant generation characteristics of the system. The types of relative motion between surfaces and spaces where movement of fluid occurs may be listed as follows:

1. Rotating shaft within a bearing
2. Linear motion of a piston, spool or shaft within a cylinder or seal
3. Rotating discs
4. Sliding plates
5. Orifices - fluid flowing past stationary parts.

These basic elements are illustrated in Fig. 4-1. The rotating shaft within a bearing is used in all types of hydraulic pumps and motors. Linear actuation characterizes the motion in hydraulic cylinders, spool valves and piston pumps. Rotating discs describe the action in practically all types of pumps and motors such as between gear pinions and wear plates and between cylinder chamber and valve plates. A sliding plate action is exhibited by the relative movement of gear tooth tips against the gear housing and also between the leading edge of a vane and the

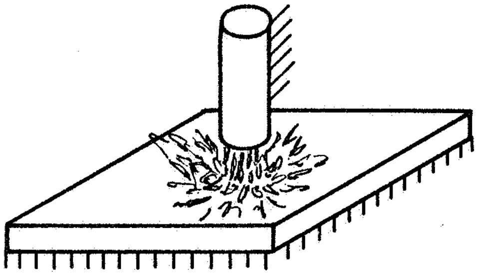
(a) ROTATING SHAFT WITHIN A BEARING

(b) LINEAR ACTUATION



(c) ROTATING DISCS

(d) SLIDING



(e) ORIFICE (erosion)

Figure 4-1. BASIC COMPONENT MECHANISMS.

inner periphery of the cam reaction ring in a vane pump. The orifice represents a fundamental configuration in all types of fluid components.

In the case of a pump, failures can generally be classified as either mechanical failures or volumetric failures. Examples of mechanical failures are wear and destruction of ball bearings, sticking and dragging of pistons in the bores, pitting and breaking of gear teeth, cracking of vanes, deterioration of vane slots, and backlash in the control linkages. In high pressure pumps the close tolerances, smooth finishes and lubrication provisions set the stage for contaminants to wedge, gouge, abrade and destroy dynamic component surfaces. The volumetric failure of a pump usually does not happen suddenly, but is rather a slow, steady process of deterioration of the unit's output. Direct and indirect damage to sealing surfaces account for volumetric failure. Examples of volumetric failures are enlargement of leakage paths, wedging apart of sealing members, and wear in guides, bearings, and retainers which cause sealing members to change position relative to each other.

4.3 ESTABLISHING CONTAMINANT TOLERANCE LEVELS

The contaminant tolerance level of a component used in a fluid system generally involves subjecting the component or element under consideration to fluids containing known quantities of specific contaminants having a particular size distribution. Essentially two types of tests are performed on a specific component:

1. Size sensitivity tests
2. Quantity sensitivity tests

In the size sensitivity test the specified contaminant is classified into fixed size ranges (such as 0-5, 5-10, 10-15, etc. microns). A specified quantity of each size range is injected into a circulating system containing the prescribed component. When the size range is reached where the component exhibits a significant change in performance, the upper size range has been established. Figure 4-2 illustrates a typical performance curve for a component when subjected to various sizes of contaminant. The contaminant size sensitivity of the component obtained in this manner establishes the size rating of the system's filter needed to protect the component.

The quantity sensitivity test determines the gravimetric amount of contaminant which the component can tolerate without influencing its performance. The size of the contaminant used in the sensitivity to quantity tests must exhibit an upper limit dictated by the size sensitivity tests. In practice, the particles in a contaminant size distribution exceeding the size sensitivity limit of the component are removed by a particle classifier. Various quantities of the prepared contaminant are subjected to the component in a circulating system. The gravimetric contamination level of the fluid where the component exhibits a significant change in performance establishes the maximum contaminant quantity which can exist in the fluid. The value of the maximum contaminant quantity as obtained from the above described test has a direct influence on the required characteristics of the system filter. In a generating system, if the filter is not capable of removing sufficient contaminant (regardless of its pore size distribution) from the fluid to stay within the specified gravimetric limit it is not suitable for the protection of the component. A curve very similar to Fig. 4-2 is obtained from the data in a quantity sensitivity test except that gravimetric levels are used in place of contaminant size.

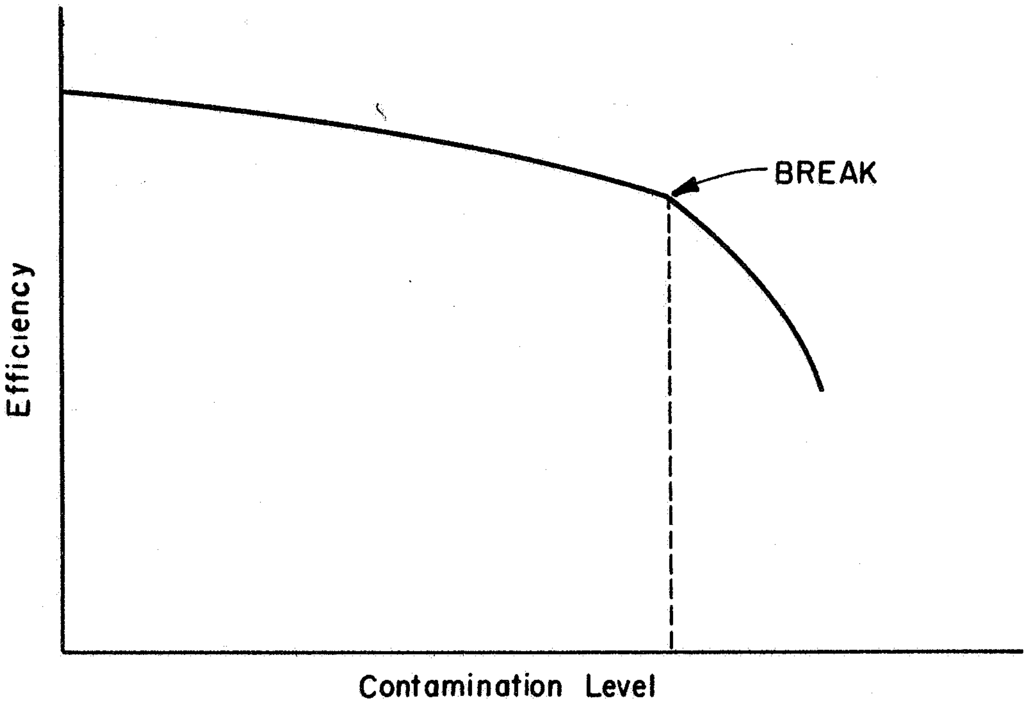


Figure 4-2. PERFORMANCE EFFICIENCY CURVE.

In order for contaminant tolerance level tests to be physically meaningful, the contaminant size and quantity sensitivities of the component must be expressed in terms relative to a cleanliness level standard. Using the Cleanliness Level Chart presented in Chapter II, a specific area of the Chart can be established as an acceptable level of contamination for the component. For example, the size sensitivity of the component can establish the maximum allowable slope of the particle size distribution curve (average particle volume line on the Chart) and the quantity sensitivity can establish the maximum allowable gravimetric bounds on the Chart. Hence, a typical contaminant tolerance level specification for a component would be indicated on the Cleanliness Level Chart as shown by the cross hatched area in Fig. 4-3. The contamination level for an acceptable fluid must exhibit cleanliness level values within the specified area on the Chart.

It should be recognized that a component such as a pressure compensated piston pump may exhibit a double size sensitivity. The normal size sensitivity expresses the maximum size distribution curve which must not be exceeded. The compensator valve may impose additional restrictions such as the gravimetric level of the particles in the fluid below say 5 microns. In this case, the slope of the distribution curve must also be limited so as not to exceed a specified quantity of low micron (silting type) particles. Such a condition can be specified on the Cleanliness Level Chart as shown in Fig. 4-4.

In order to establish the contaminant tolerance levels of hydraulic components, operational parameters must be defined and used from which to appraise changes in the performance and reliability of the component.

OSU LEVEL	GRAVIMETRIC	VOLUME
00	0.010	2.8
02	0.016	2.9
04	0.025	3.0
06	0.040	3.1
08	0.063	3.2
10	0.10	3.4
12	0.16	3.5
14	0.25	3.7
16	0.40	3.9
18	0.63	4.2
20	1.0	4.5
22	1.6	4.8
24	2.5	5.2
26	4.0	5.6
28	6.3	6.2
30	10	6.8
32	16	7.7
34	25	8.8
36	40	10.2
38	63	12.2
40	100	15.0
42	160	19.3
44	250	26.3
46	400	38.6
48	630	64.0
50	1000	127.0
52	1600	349.0
54	2500	1797.0
56	4000	43773.0
58	6300	∞--
60	10000	∞

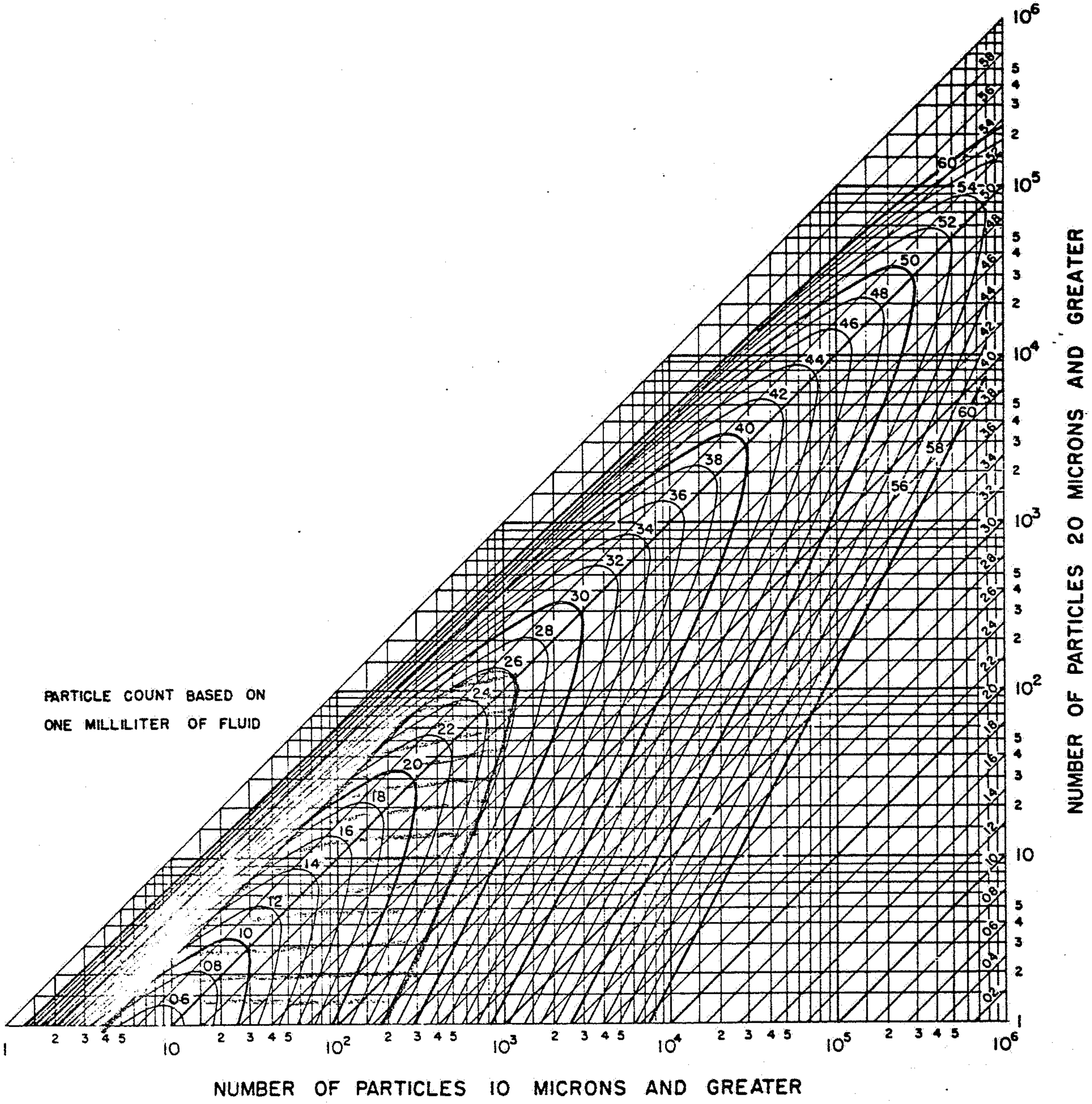


Figure 4-3. Contaminant Tolerance Specification.

OSU LEVEL	GRAVIMETRIC	VOLUME
00	0.010	2.8
02	0.016	2.9
04	0.025	3.0
06	0.040	3.1
08	0.063	3.2
10	0.10	3.4
12	0.16	3.5
14	0.25	3.7
16	0.40	3.9
18	0.63	4.2
20	1.0	4.5
22	1.6	4.8
24	2.5	5.2
26	4.0	5.6
28	6.3	6.2
30	10	6.8
32	16	7.7
34	25	8.8
36	40	10.2
38	63	12.2
40	100	15.0
42	160	19.3
44	250	26.3
46	400	38.6
48	630	64.0
50	1000	127.0
52	1600	349.0
54	2500	1797.0
56	4000	43773.0
58	6300	∞--
60	10000	∞

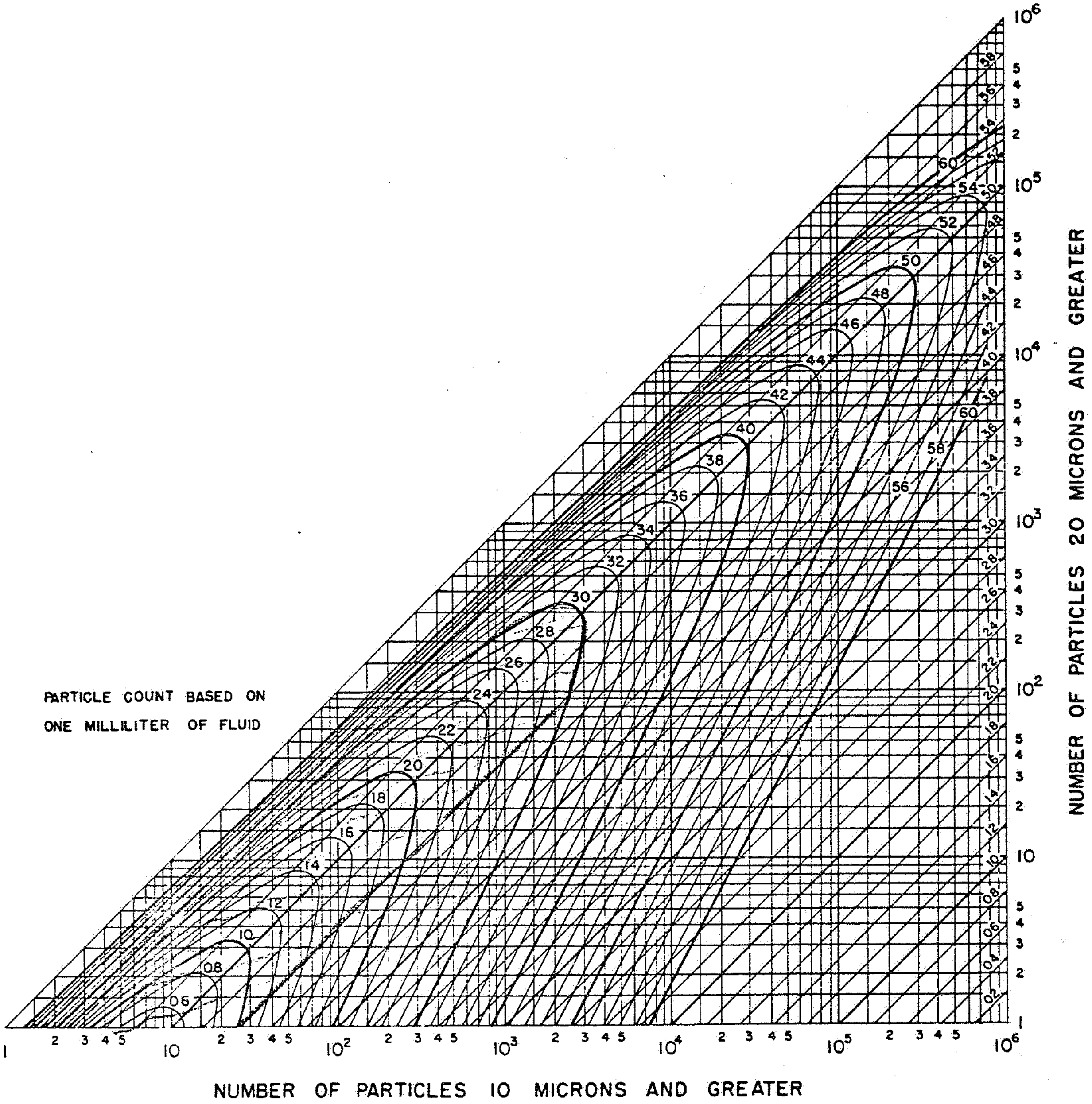


Figure 4-4. Contaminant Tolerance Level Specification,

Operational or performance parameters which have been used to measure and detect the effects of contamination on components are as follows:

1. Mechanical Efficiency
2. Volumetric Efficiency
3. Valve Hysteresis
4. Actuating Force
5. Actuating Torque
6. Change in Leakage
7. Contaminant Generation
8. Creep Characteristics in Cylinders
9. Time to Stick a Valve

In most tests, it is wise to employ more than one performance criteria unless experience has shown that one parameter is sufficient. For example, in a fixed displacement pump, the mechanical and volumetric efficiencies have been demonstrated to be quite adequate for use as operational parameters.

Pump and motor contaminant tolerance level tests are of necessity a destructive type test. This is due to the fact that the change in performance parameters results from the partial self destruction of the component. Clearance spaces are enlarged by the contaminant as a result of the operation of the component. To date, no satisfactory test has been developed for high speed rotating machinery to circumvent the destruction of the component.

Non-destructive tests are feasible for components such as valves. In this case, operational parameters are available to measure the change in performance which does not depend upon the deterioration of the parts of the component. Hence for a valve, an increase in the actuating force necessary to open the ports is not in itself related to the destruction of the component's surfaces. The silting nature of a valve or its susceptibility to sticking is of prime importance in specifying the contaminant tolerance level.

The most contaminant sensitive element within a component establishes the contaminant tolerance level for the component. This concept also applies to a system because the most contaminant sensitive component in the system establishes the contamination level limits for the entire system. Hence, the importance of contaminant tolerance level research can be appreciated since it may lead to the overall relaxation of contamination level limits.

4.4 PRELIMINARY EXPERIMENTAL WORK

Exploratory studies directly concerned with the contaminant tolerance levels of fluid components have been conducted at Oklahoma State University since 1963. Mr. M. L. Wolf (5) developed the first procedure for measuring the contaminant tolerance levels for pumps while a graduate student at OSU. Modifications to Wolf's procedure have resulted in a simple test yielding data that have a direct correlation with the contamination level of a system. The operational parameters employed by Wolf and subsequent investigators of pumps were the mechanical and volumetric efficiency. Test results exhibited significant breaks in the performance curves when the size and quantity sensitivity limits were reached. Preliminary work on pumps has included tolerance studies for gear, vane and piston types. Field results have correlated exceptionally well with the established laboratory test limits. In addition, the contaminant tolerance tests have proved very useful in appraising the effectiveness of various bearing designs.

Experimental work on the contaminant tolerance levels of hydraulic cylinders has been conducted over the past two years. Since cylinders subjected to high levels of contamination tend to generate particles due to the deterioration of the walls of the cylinder, it was reasoned that changes in particle size distribution might be a valid operational parameter. Test results have not substantiated this premise because the generated particles do not produce a significant change in the overall contamination level of the fluid. The most reliable performance parameter for cylinders appears to be a creep test. This test measures the effective change in fluid leakage across the piston. In the cylinder tests, the cylinder being investigated is cycled by means of a drive cylinder.

Most of the preliminary experimental work at OSU on contaminant tolerance levels has been associated with valves. The time required to cause sticking of a valve force that is periodically activated by a fixed magnitude has been extensively employed as an operational parameter to appraise valve performance. Various types of contaminant, contaminant sizes, distributions and quantities have been applied with a high degree of success. In one typical case, a spool valve having a radical clearance of 0.0002 inches was tested on a time to stick basis with various sizes of contaminant. The valve did not show any significant sensitivity to contaminant except in the 0-5 micron size. Tests were then conducted with various quantities of 0-5 micron contaminant which produced the results shown in Fig. 4-5.

In another case, a valve with a 0.0002 inch radial clearance was tested that contained provisions for measuring the actuating force or stroking force of the valve. The valve was subjected to various types,

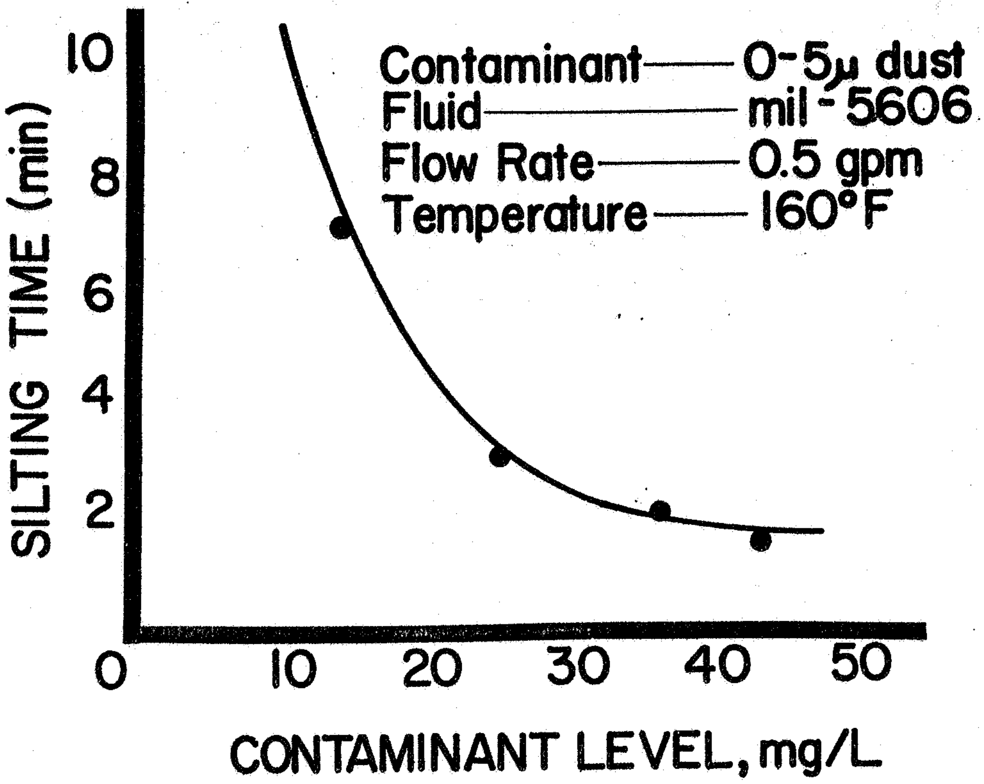


Figure 4-5. Contaminant Quantity Tolerance Curve for a Valve.

size distributions, and quantities of contaminants. The force versus time curve under various conditions was established for the valve, and a typical representation of this data is presented in Fig. 4-6. The curves in Fig. 4-6 represent various gravimetric levels of a 50:50 mixture of A.C. Fine Test Dust and Carbonyl Iron E (4-6 microns). The percent stroking force used in Fig. 4-6 is the ratio of the actual stroking force to the maximum available stroking force.

One of the purposes in conducting the exploratory and preliminary experimental work was to discover a proper direction for future studies in contamination tolerance levels. The ultimate goal being to establish dependable design techniques which would lead to the relaxation of tolerance levels and to develop realistic tests for contamination control purposes. The results from experimental work on three matched valves, possessing radial clearances of 1¼, 2½ and 5 microns, respectively, gave encouraging evidence that the ultimate goal could be achieved. The silting time to 50% valve sticking was measured for each valve with various quantities of contaminant. The results indicated that a critical clearance existed for a specific contaminant regardless of the quantity injected. A representative graph of this data for Carbonyl Iron is presented in Fig. 4-7. The tests on these valves have also revealed the effect of contaminant type on the tolerance level of such components. In addition, evidence came to light from these tests which establishes the direction needed for relaxing contaminant tolerance levels for valves and piston pumps. It was with this background information that the current experimental test program was initiated.

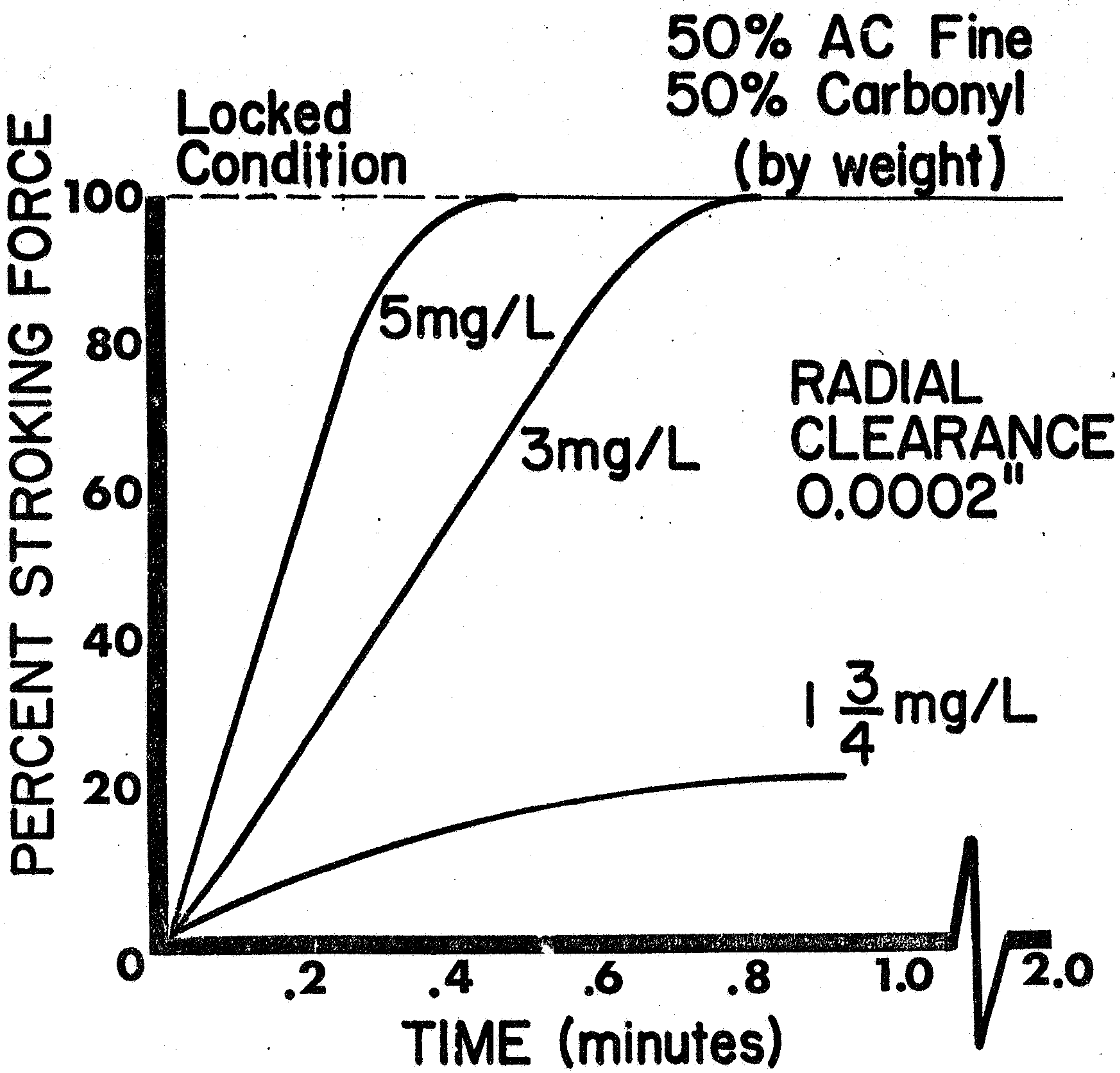


Figure 4-6 Contaminant Quantity Tolerance Curves for a Valve Using Stroking Force as a Parameter.

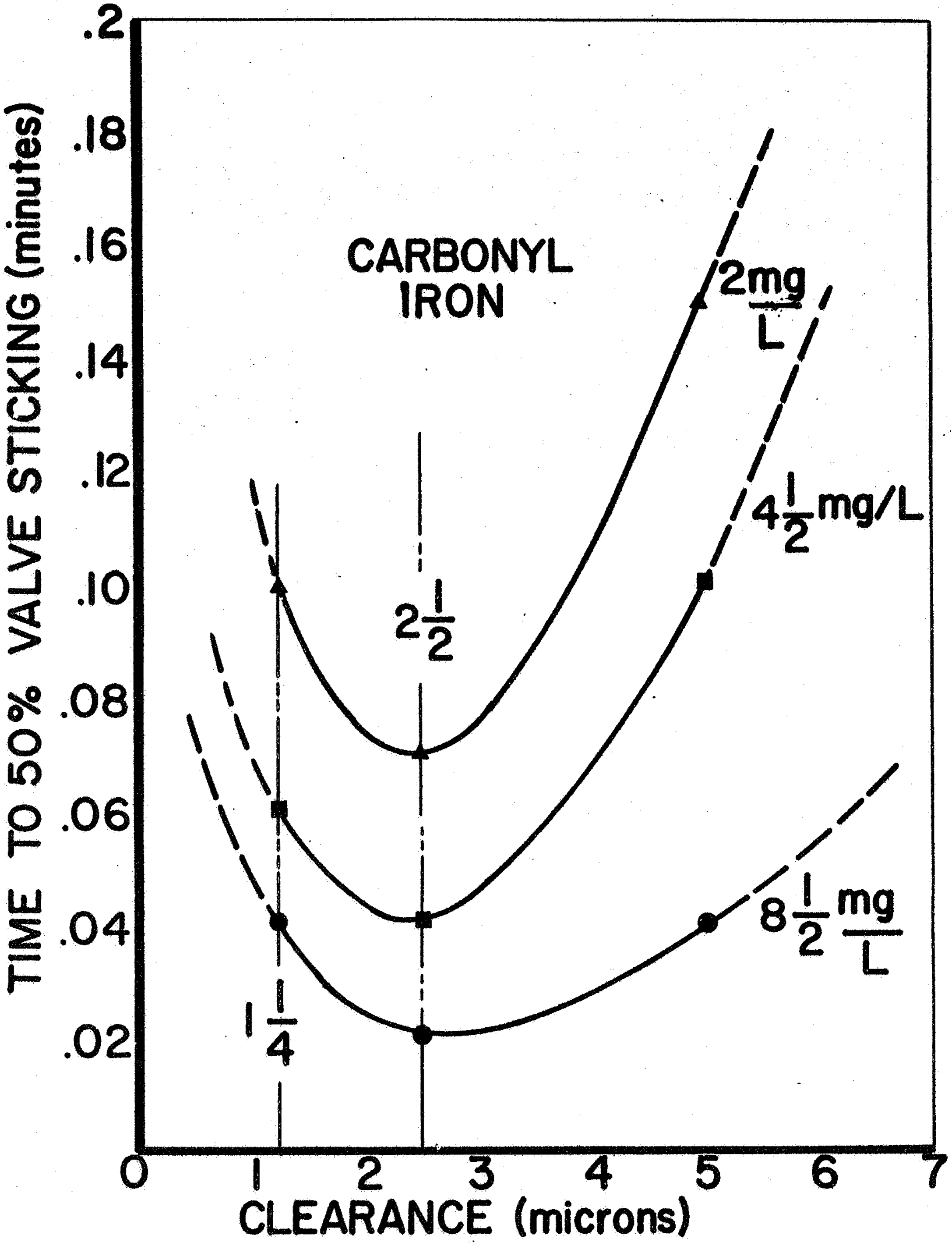


Figure 4-7. Contaminant Quantity Tolerance Curves for 50% Valve Using Carbonyl Iron.

4.5 CURRENT EXPERIMENTAL WORK

The interactions that take place between the mechanical fluid power components and the power transmission medium (the fluid) are not absolutely understood today, not to mention the relative effects of contamination that are also transmitted by means of the fluid. The behavior of fluids, compounded with existing contamination, in minute spaces relative to dynamic boundaries appears to be complex, and the area deserves more research.

Nevertheless, previous work at OSU, et al, has indicated some validity of using component clearance spaces as a means to detect or otherwise evaluate contamination levels. Accordingly, it was theorized that a discrete contamination level should exhibit a measurable affect upon the controlled operation of a valve having a fixed clearance. Hence, the effect could be expressed in terms of the valve's frictional sensitivity, correlated with clearances, to contamination levels. Ultimately, a contamination tolerance level would be established for the configuration of the valve and the conditions of the test.

The problem was to design and develop a test fixture in which clearance, surface finishes, materials, and configurations could be varied and still permit proper interpretation of its performance. A valve concept of Dr. E. C. Fitch was selected, which would allow clearances to be varied within a spool land chamber from zero to any value necessary for the test.

Preliminary Leakage vs. Clearance

The valve test fixture shown in Fig. 4-8 was designed to permit various levels of contaminated fluid to pass through the test ports. Leakage fluid would flow in the annular spaces past the top and bottom

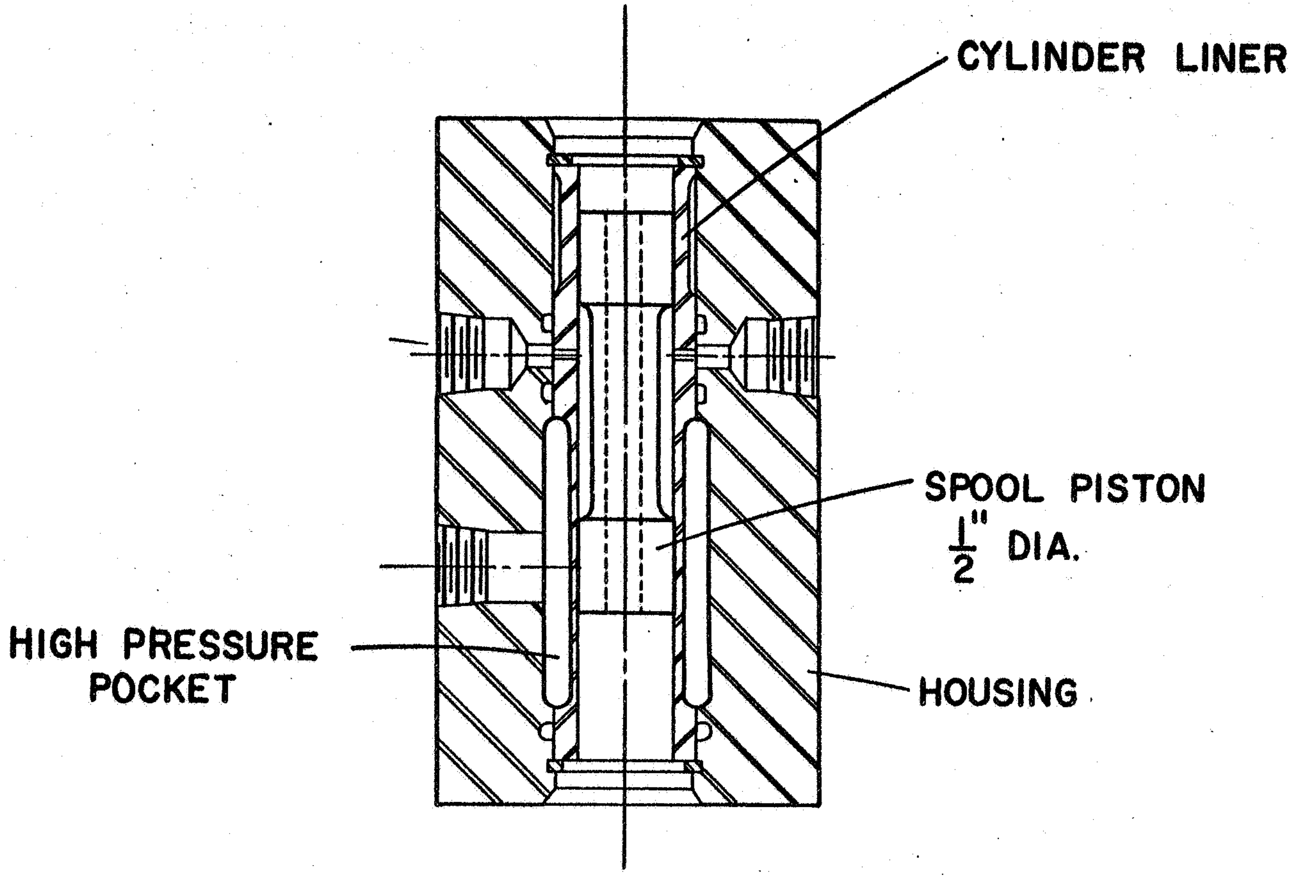


Figure 4-8. Variable Piston Clearance Device.

lands of the spool. Provision was made to vary the clearance at the bottom land by establishing independent fluid pressures in the sleeve chamber. The sleeve chamber pressure, the thickness of the sleeve around the bottom land, and the internal system pressure would influence the resulting clearance valves. Hence, a quantitative measure of the clearance could be obtained from measurements of the associated leakage fluid.

In order to verify the utility of the concept of the variable clearance test fixture, the theoretically designed assembly was fabricated at OSU. Special honing equipment was not used at that time because of the experimental state of the idea. The fixture was tested for its ability to respond in clearance variations in correlation to changes of sleeve chamber pressure. A system pressure of 1000 psi was introduced to the valve, sleeve pressure varied, and leakage flow recorded. Fig. 4-9 shows the results of these tests. As can be noted from the graph, a linear flow characteristic was indicated.

The clearance was calculated from the following Leakage Flow Rate Theory: it is well known that the leakage flow rate through an annular clearance between a piston and bore of a hydraulic oil pump, motor, or valve is proportional to the cube of the clearance. For situations where the piston and bore are essentially circular, parallel with surfaces and axes, the basic flow relationship can be expressed by

$$Q_x = \frac{\pi D C^3}{96 \mu} \cdot \frac{\partial p}{\partial x} \quad (1 + 1.5 \epsilon^2) \qquad (4\text{-}1)$$

and if axial pressure drop is assumed linear,

$$Q_x = \frac{\pi D C^3 P}{96 \mu L} \cdot \quad (1 + 1.5 \epsilon^2) \qquad (4\text{-}2)$$

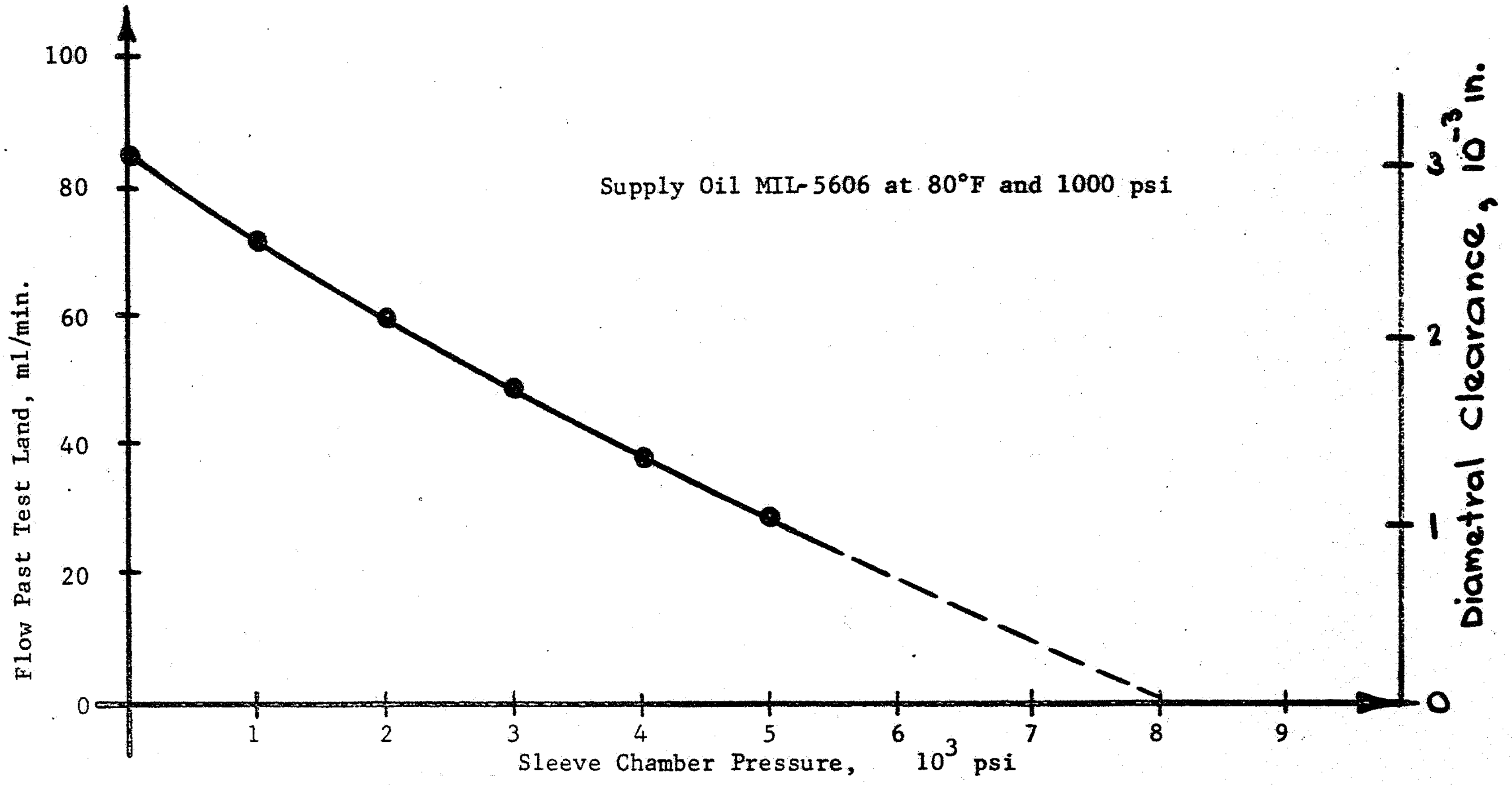


Figure 4-9. Leakage Characteristic of Variable Clearance Fixture.

where all variables are in lb. ft. sec. units and Q is the leakage flow rate in ft.^{3}/sec.; D is the nominal diameter of piston and bore; C is the nominal diametral clearance between piston and bore; is the absolute viscosity of the oil; L is the length of the piston land; x refers to the axial direction; p (implicit in Eq. 4-1) is the pressure at any point in the clearance annulus; $\epsilon = 2e/C$ is the eccentricity ratio describing the radial position of the piston in the bore; e is the radial displacement of the piston and bore axes; P is the axial pressure drop along the piston land. Of course, P is given by the supply pressure if the discharge pressure is zero.

Figure 4-10 shows the general piston attitude referred to, together with the limit cases of full concentricity and full eccentricity. The factor $(1 + 1.5\epsilon^2)$ has a value of 1 for perfect concentricity and 2.5 for full eccentricity, showing the range of leakage variation with the other parameters held constant.

Using more conventional leakage flow units, Eq. (4-2) becomes

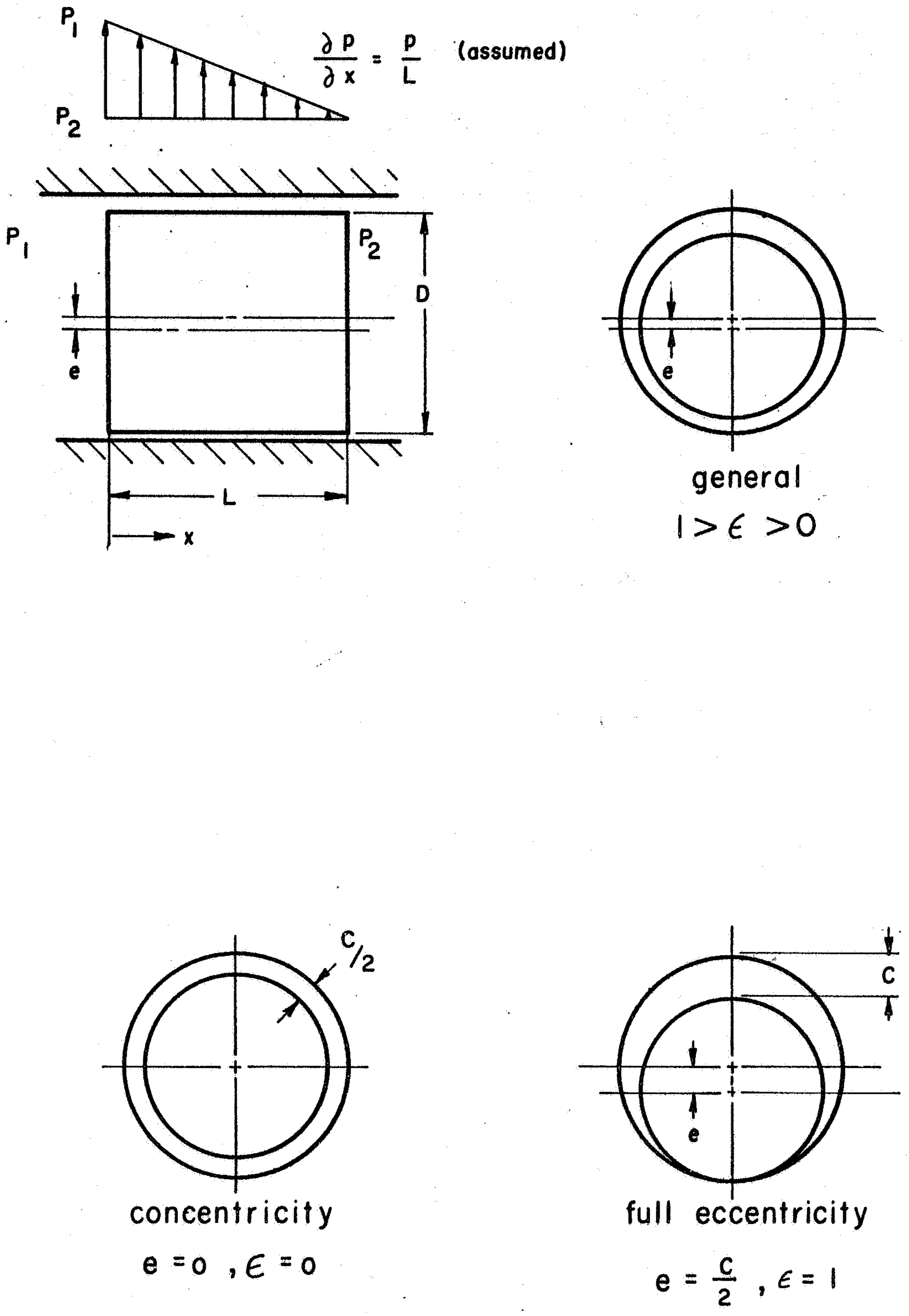
$$Q_x = \frac{13.55 \times 10^6 D C^3 P}{\mu L} (1 + 1.5\epsilon^2) \text{ in}^3\text{/min.} \qquad (4\text{-}3)$$

where D and L are expressed in inches, P in lb/in^2, C in 10^{-4} inches, and viscosity μ is in centipoises.

Preliminary Valve Performance

Further testing, by means of a test fixture as illustrated by Fig. 4-11, indicated that pistons can experience frictional conditions in their bores from one or more of the following three causes:

1. Hydraulic lock - the presence of a de-centering lateral force on the piston due to asymetrical pressure distributions along



general

$1 > \epsilon > 0$

concentricity

$e = 0, \epsilon = 0$

full eccentricity

$e = \frac{C}{2}, \epsilon = 1$

Figure 4-10

Piston – Cylinder Configuration

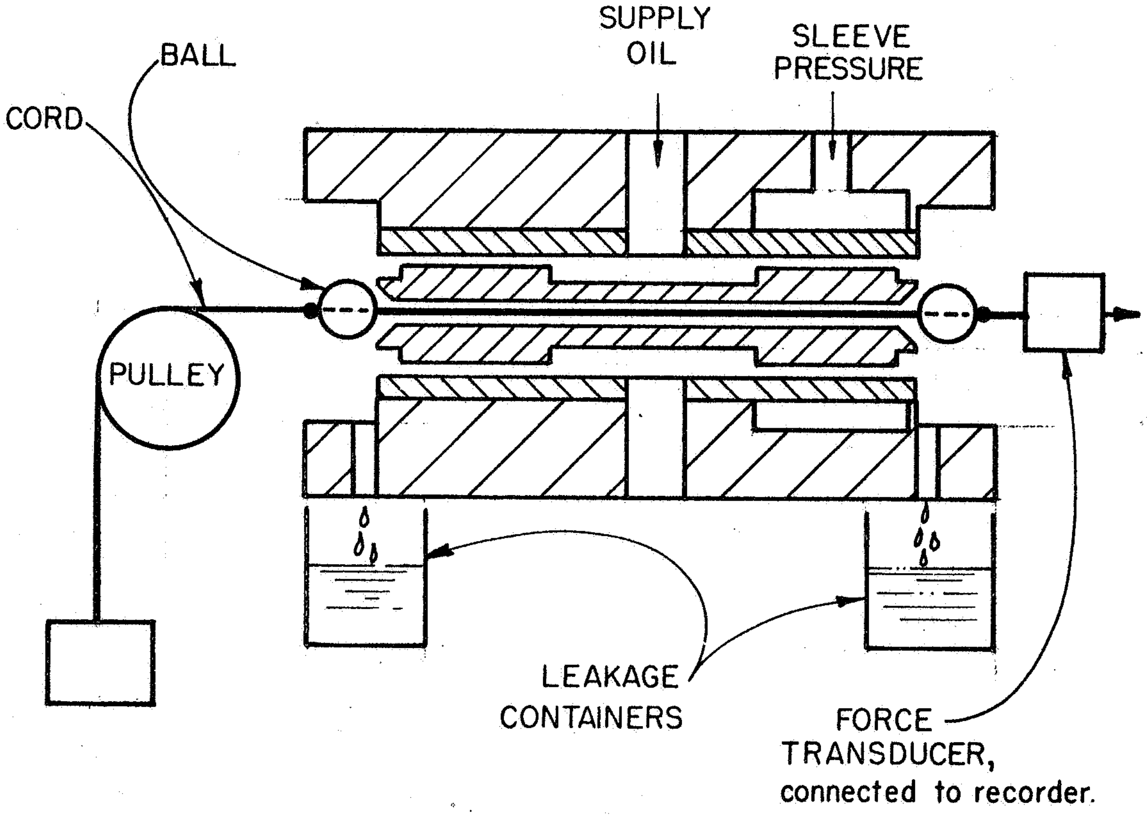


Figure 4.11– SET-UP FOR MEASURING BREAK-OUT FORCE ON PISTON.

the piston, and manifests itself as a frictional resistance to motion.

2. Thermal Lock - physical interference between the piston and its bore, due to the expansion-contraction effects of temperature differentials across the components.
3. Contamination Lock - an interference phenomena due to the presence of hard particles of contaminant in and around the clearance space between piston and bore. The contaminant particles can be forced into the clearance in the leakage flow due to the axial pressure drop along the piston land, as well as taken in by means of viscous drag.

The term "lock," although commonly used, may be an overstatement of the phenomena described. Lock can vary from a barely perceptible stick-slip feeling to complete jamming. With some sensitive components, even a slight degree of sticking seriously affects their performance.

The Viscosity-Temperature-Pressure Characteristics of MIL-5606

In this research area, it became apparent that viscosity is a most important parameter used in assessing the performance and losses at many points in a system (fluid line losses, clearance leakage losses, pump and motor efficiencies, etc.). The viscosity of the oil is affected by both temperature and pressure. It is most desirable that one establish the temperature-pressure-viscosity characteristics of a system's hydraulic fluid. Usually, calculations of viscosity are made using the empirical isothermal and isobaric relationships,

$$\mu = \mu_o e^{\psi P} \text{ (isothermal)}; \quad \mu = \mu_o \left(\frac{T_o}{T}\right)^k \text{ (isobaric)} \qquad (4\text{-}4)$$

where the coefficients ψ and k of the oil must be obtained. In connection with the work reported herein, the μ-T-P relationships of MIL-5606 fluid were necessary to the understanding of, and to the utilization of the performance and clearance assessments required in the referenced research. A description of the experimental evaluation of the viscosity characteristics, in the pressure and temperature ranges of 0 - 10,000 psi and 70 - 300°F, is respectively presented.

A Ruska High Pressure Viscometer was used. This unit, illustrated in Fig. 4-12, automatically measures the time of the fall of a ball rolling down an inclined tube as the measure of the viscosity of the fluid in the tube. The tube can be pressurized to 10,000 psi, and it is jacketed to enable steady state temperatures to 300°F to be achieved. The temperature control is automatic, with a desired value setting. In the ready position, the steel ball (about 0.250 inches in diameter) is held magnetically at the top of the tube (0.312 inch bore). A switch releases the ball and starts the timer simultaneously. The timer stops automatically when the ball reaches the lower end of the tube. The viscometer can be given any of three angles of inclination (23°, 45°, and 70°), allowing for a wide range of viscosity measurement.

The viscosity readings obtained in terms of seconds, here referred to as θ° Ruska seconds, where θ° is the angle of inclination used. Figure 4-13 shows the 70° Ruska seconds versus pressure results obtained for 5606 over a range of temperatures. As semi-log plots, the variations in readings, at discrete temperature values, are seen to be linear but not parallel. An identical family of curves was obtained with a 45° angle of inclination, except that they were displaced upwards on the time scale (longer fall time).

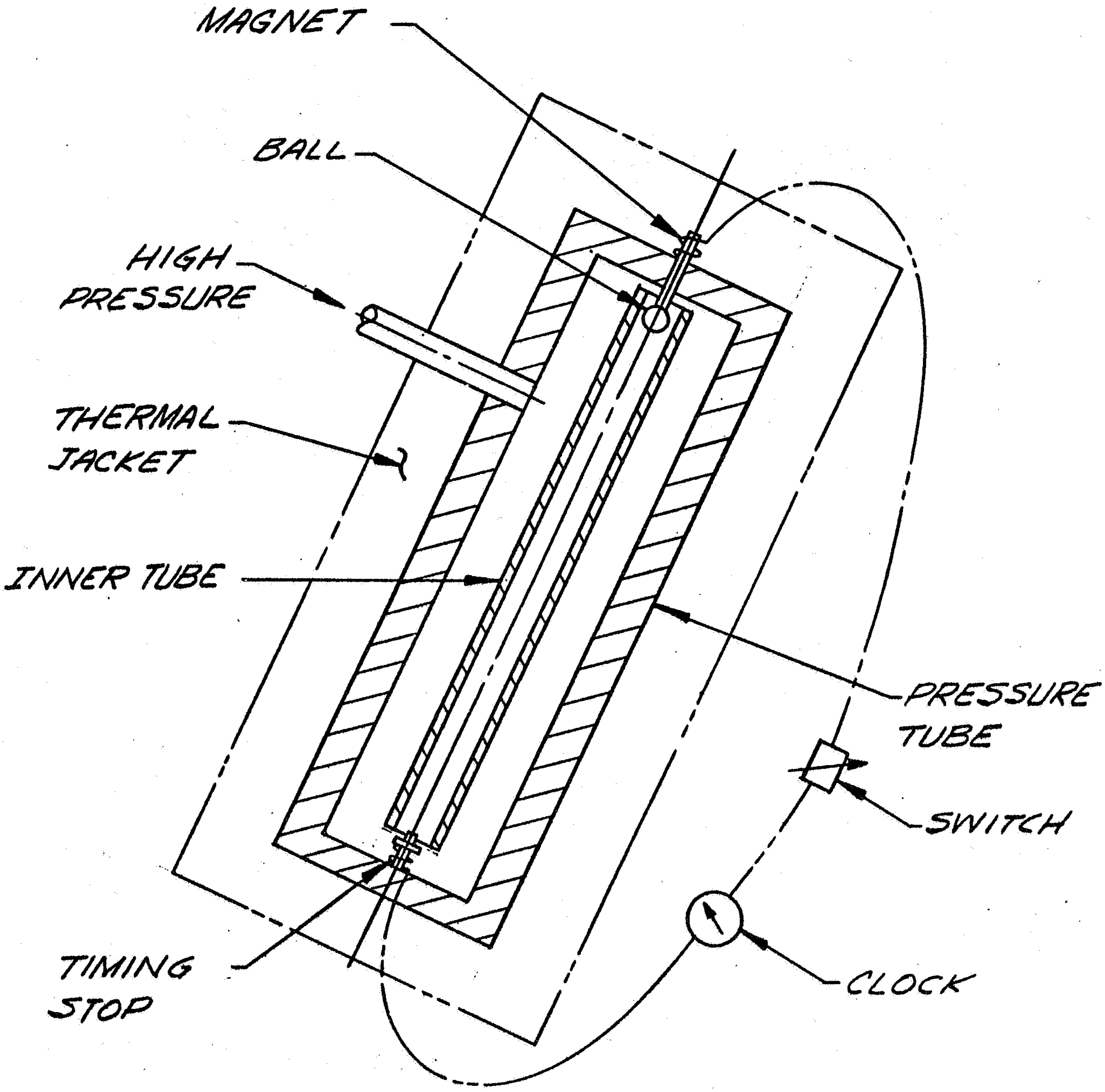
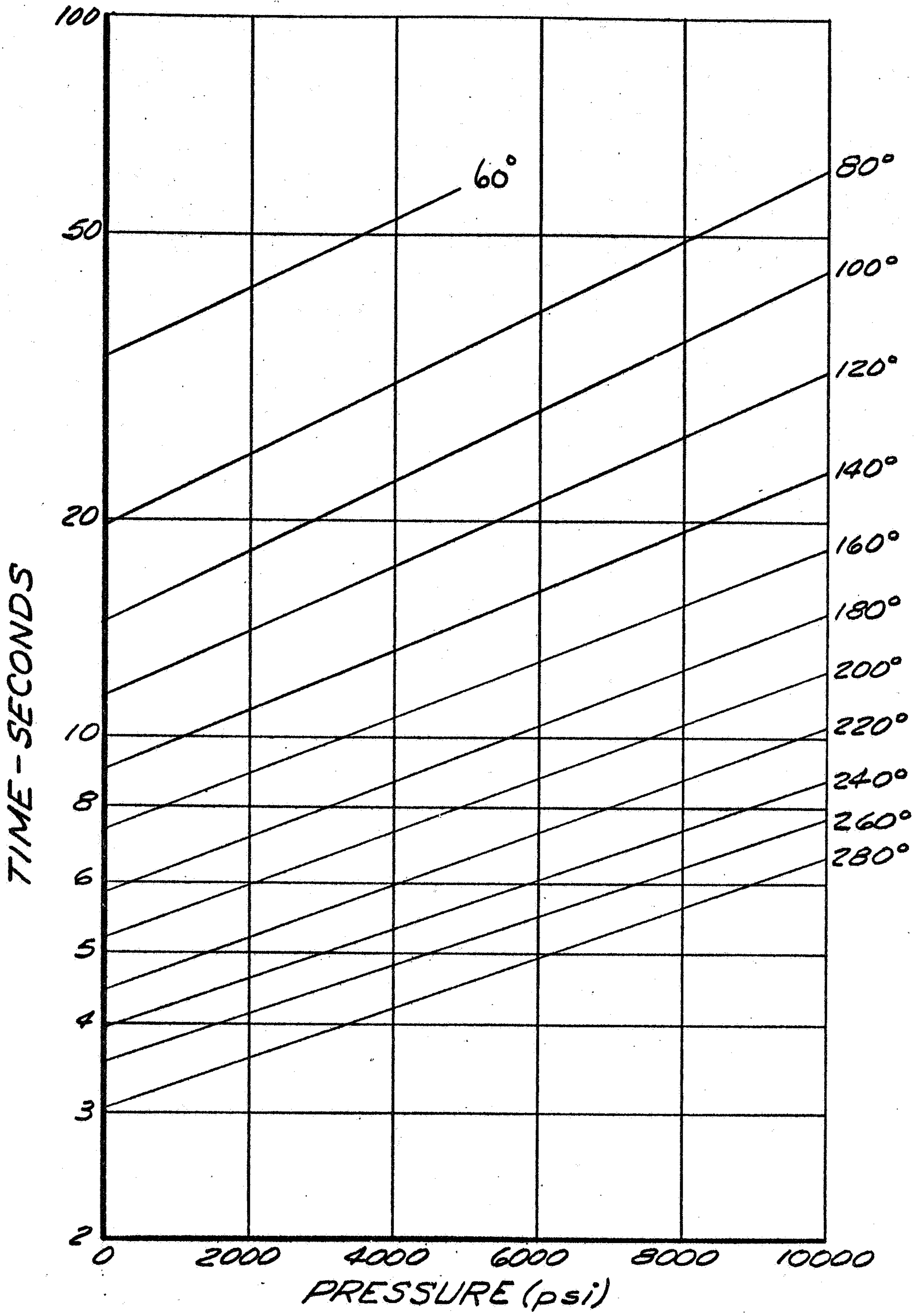


DIAGRAM OF PRINCIPLE OF RUSKA HIGH PRESSURE VISCOMETER

Figure 4-12.



TIME VS PRESSURE
Rusko Viscometer, 70° Angle

Figure 4-13.

In order to get the viscosity on an absolute scale (centipoises), an atmospheric-pressure-viscosity-temperature curve was obtained using a Brookfield viscometer. Figure 4-14 shows this curve, obtained by using two samples of new 5606 oil from two independent manufacturers. The measured results were similar at least to the degree that Fig. 4-14 represents both oils with no measurable discrepancy.

Values of viscosity from Fig. 4-14 were correlated with the 70° Ruska second readings on the zero pressure ordinate of Fig. 4-13. It was found that the centipoise scale so established was a log-log scale. Then, using log-log (viscosity) versus linear (pressure) coordinates, and taking constant viscosity values of temperature and pressure from Fig. 4-13, points of constant temperature were plotted on Fig. 4-15. These points yielded the family of parallel isothermal lines shown on Fig. 4-15. The equation for these curves is

$$\log(\log \mu) = 0.000015\,P - 0.569 \log \frac{T}{122} \qquad (4\text{-}5)$$

where μ is the viscosity at P, T, in centipoises; P is the pressure, psi, T is the temperature F.

The equation was computerized, and the T-P-μ characteristics of Fig. 4-16 were calculated. Figure 4-16 and Fig. 4-15 (the experimental results) are virtually identical.

The rate of fall of the ball in the tube of the viscometer is dependent on the clearance between the ball and the bore. If the high pressures used should expand this clearance, the correlation between readings of viscosity taken with the Brookfield viscometer at atmospheric pressure, and high pressure results from the Ruska unit would be invalid. However, the operation of the Ruska unit is such that the pressure on

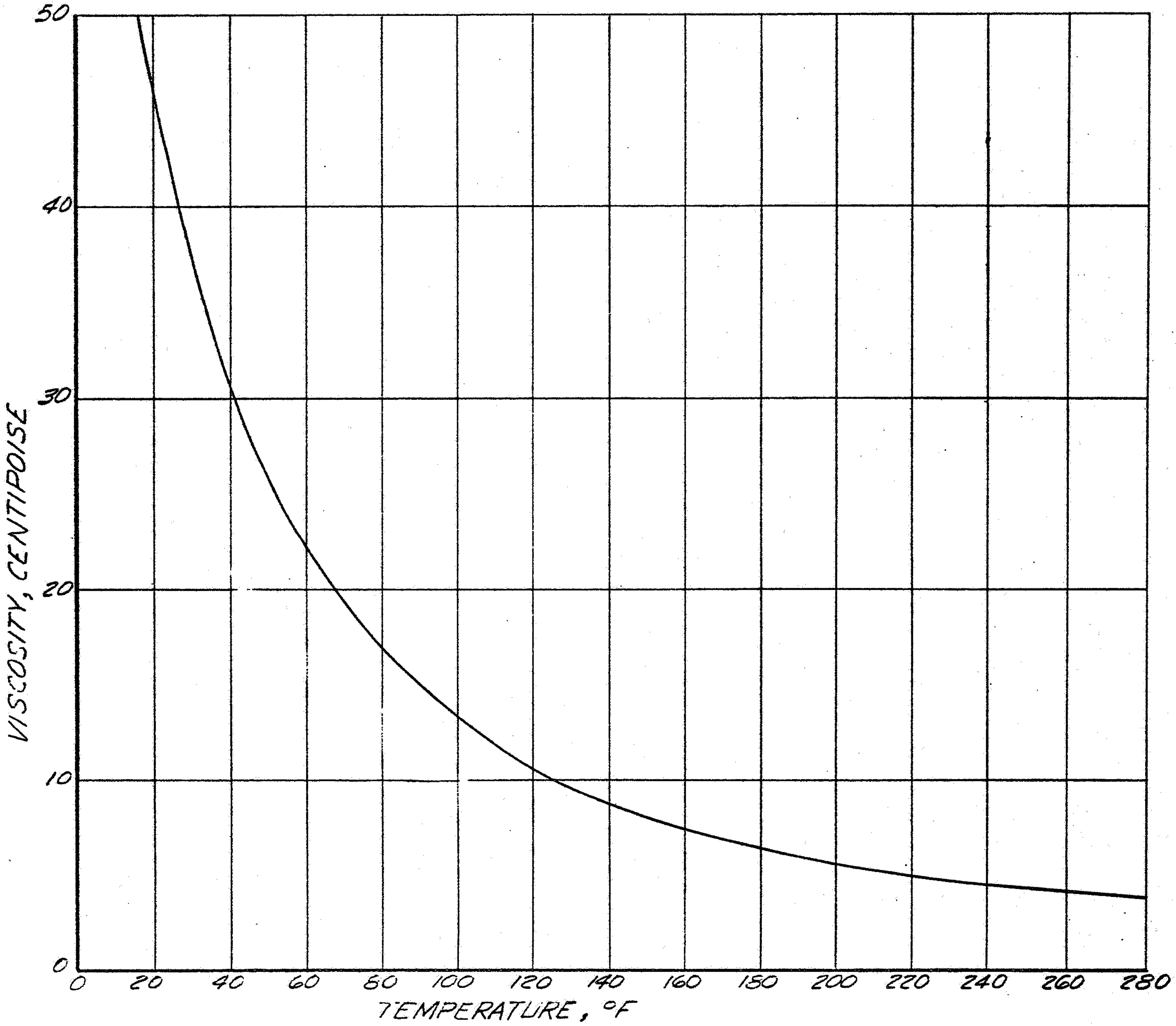
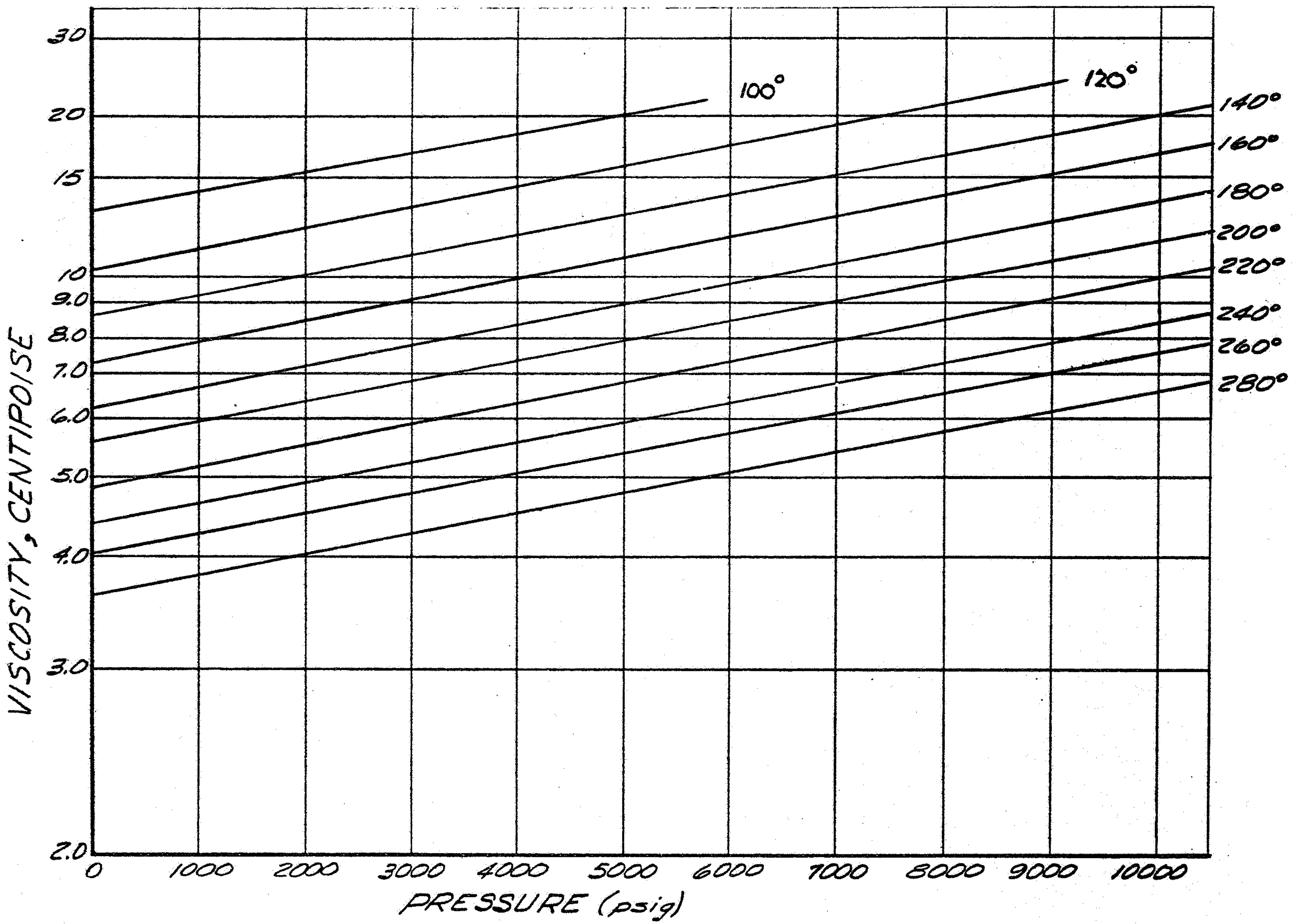
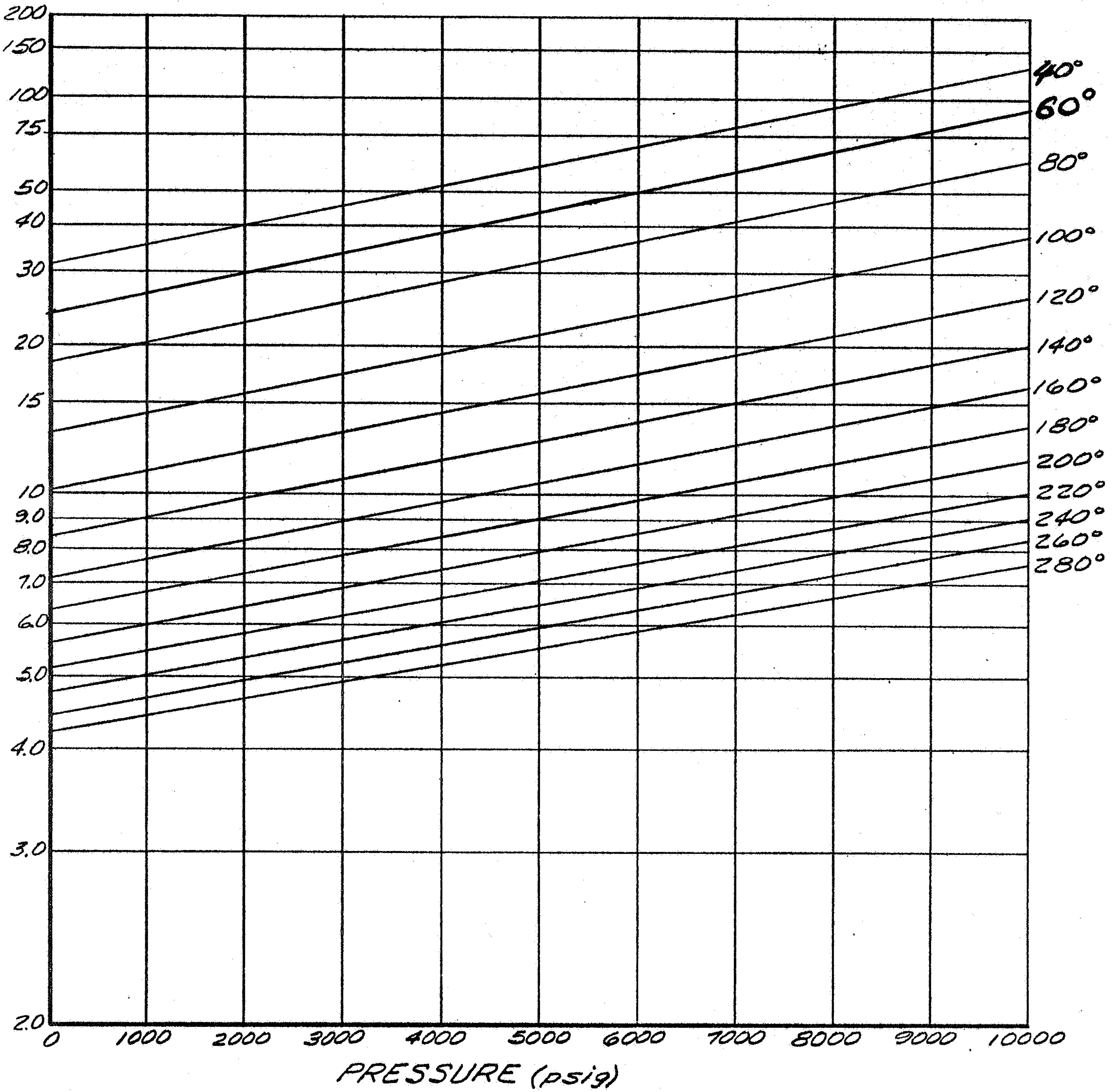


FIGURE 4-14
Viscosity of Mil 5606 at Atmospheric Pressure.
(Brookfield Viscometer).



VISCOSITY-PRESSURE-TEMPERATURE, MIL 5606
MEASURED DATA

FIGURE 4-15



VISCOSITY-PRESSURE-TEMPERATURE, MIL 5606
CALCULATED DATA

FIGURE 4-16

the outside of the tube is the same as in the bore. Hence, no pressure expansion of the bore takes place. The effect of pressure in changes to the volume of the ball is negligible. Hence, the clearance between ball and tube is insensitive to pressure. That is, the time the ball's travel is unaffected by pressure expansions of the clearance. The temperature of the oil will affect both the tube bore diameter and the ball diameter. If the temperature effect causes the clearance to vary significantly, the viscosity correlation is affected. The thick-wall cylinder radial temperature-strain relationship can be used to explain this phenomena as follows:

$$\Delta r = \frac{\alpha}{r(1-\sigma)}\left[(1+\sigma)\int_{r_i}^{r} Tr\,dr + \frac{(1-3\sigma)r^2+r_i^2\,(1+\sigma)}{r_i^2 - r_o^2}\int_{r_i}^{r_o} Tr\,dr\right] \qquad (4\text{-}6)$$

where: α is the coefficient of thermal expansion; σ is Poisson Ratio; T (r) is temperature gradient. Equation (4-6) reduces to

$$\Delta r_i = \alpha r_i T \qquad (4\text{-}7)$$

for an equilibrium temperature and a fixed internal radius. The solid sphere radial strain relationship is

$$\Delta r = \alpha\left(\frac{3\lambda + 2\mu}{\lambda + 2\mu}\right)\left\{\frac{1}{r^2}\int_{o}^{r} Tr^2 dr + \frac{4\lambda}{(3\lambda + 2\mu)}\,\frac{r}{r_o^3}\int_{o}^{r_o} Tr^2 dr\right\} \qquad (4\text{-}8)$$

where: $\lambda = \frac{\sigma E}{(1+\sigma)(1-2\sigma)}$, and $\mu = \frac{E}{2(1+\sigma)} = G$

are Lame elastic constants. Equation (4-6) reduces to

$$\Delta r_o = \alpha r_o T \qquad (4\text{-}9)$$

for the steel ball, where $r = r_o$ for a given steady state temperature.

Thus, temperature expansions of the tube bore and of the ball are identical, leaving the clearance and hence the drag on the ball, unaffected.

Equation (4-5) and Fig. 4-16 describe the temperature-pressure-viscosity characteristics of MIL-5606 Hydraulic Oil in the ranges of 0 - 10,000 psi and 60 - 300°F.

Deduced Approach

In view of the preliminary work, an attempt to obtain repeatable valve performance results and to have these results reflect only a contamination correlation, which is the objective of this contamination tolerance level study, the causes of thermal and hydraulic lock had to be eliminated, and clean oil had to be available.

Steps to eliminate the causes, mentioned previously, of thermal and hydraulic lock, and to provide a source of "clean" oil were as follows:

1. Engage a reputable company, Cincinnati Milling Machine Company, to construct a precision variable-clearance device using identical material for the sleeve and the spool.
2. Use a low leakage pressure drop across the spool land.
3. Design and construct a non-generating oil supply system.

Earlier work had shown that a precision device would serve to eliminate valve sticking due to thermal and hydraulic lock. Precision grinding and lapping were used to create a spool valve assembly that was well within concentricity limits. Precision fabrication also minimized surface contact between the sleeve and the spool land. The possibility of valve sticking through surface contact can be amplified by a high temperature change across the spool land. This temperature change may result from the pressure drop causing the leakage flow. Therefore, by decreasing the pressure drop across the spool land the corresponding temperature gradient is reduced and the possibility of thermal lock is decreased. The decrease in leakage pressure also substantially decreases the possibility of hydraulic lock.

Test Procedure

1. Leakage vs. Clearance Calibration - The variable clearance device was calibrated with clean oil which was supplied by the non-generating stand described previously in Chapter II. The variable clearance fixture is shown in Fig. 4-17. The non-generating stand produces a low pressure insuring that a low pressure drop exists across the spool land. High pressure oil is supplied by a single piston pressure intensifier and compresses the sleeve around one land of the spool. Hence, the clearance between the sleeve and the spool land is variable. The leakage is collected in graduated cylinders while the time for a particular quantity is measured. From this data, flow rate and clearance were calculated. The calibration resulted in correlating a leakage rate (Q in ml/min.) with the sleeve pressure (P in psig) and a calculated clearance (C in 10^{-4} in.). Table 4-1 lists this data while Fig. 4-18 graphically displays the correlation.

2. Clearance vs. Actuating Force Calibration - Supplying clean oil from the non-generating stand to the fixture shown in Fig. 4-17 also provides data for correlating the clearance of the variable clearance device with an actuating force. The actuating force was read in terms of milivolts output from the force transducer by means of appropriate read out equipment. Again, different clearances were obtained by increasing the sleeve pressure which compresses the sleeve.

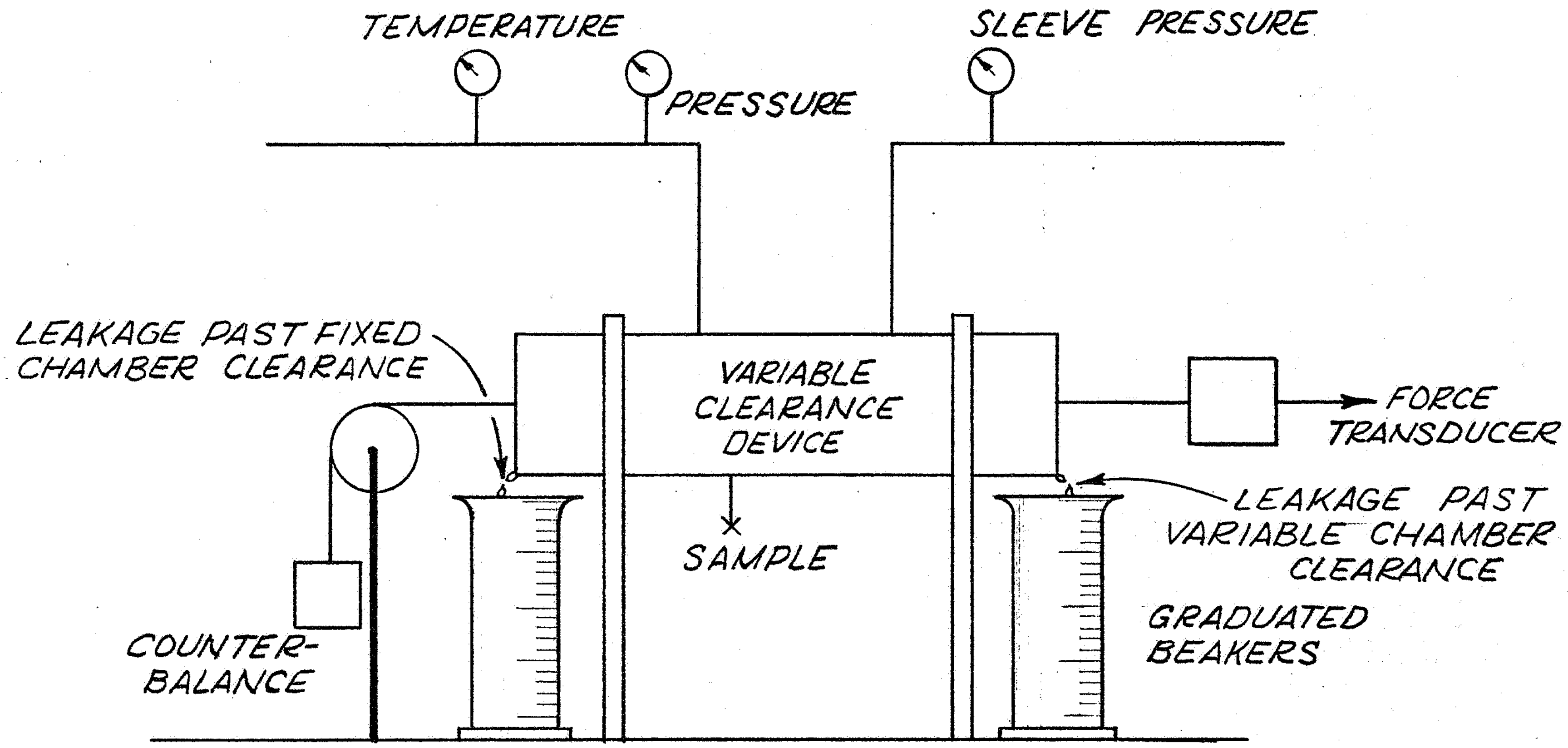


Figure 4-17. Variable Clearance Valve Test Fixture.

TABLE 4-1

LEAKAGE CALIBRATION OF VARIABLE CLEARANCE DEVICE
MIL 5606 OIL, 78°F

Sleeve Pressure (Psig)	Leakage (Ml/min)	Calculated Clearance in inches x 10^{-4}
0	0.60	13.1
500	0.42	11.6
1000	0.27	10.0
1500	0.20	9.1
2000	1.13	7.9
2500	0.08	6.7

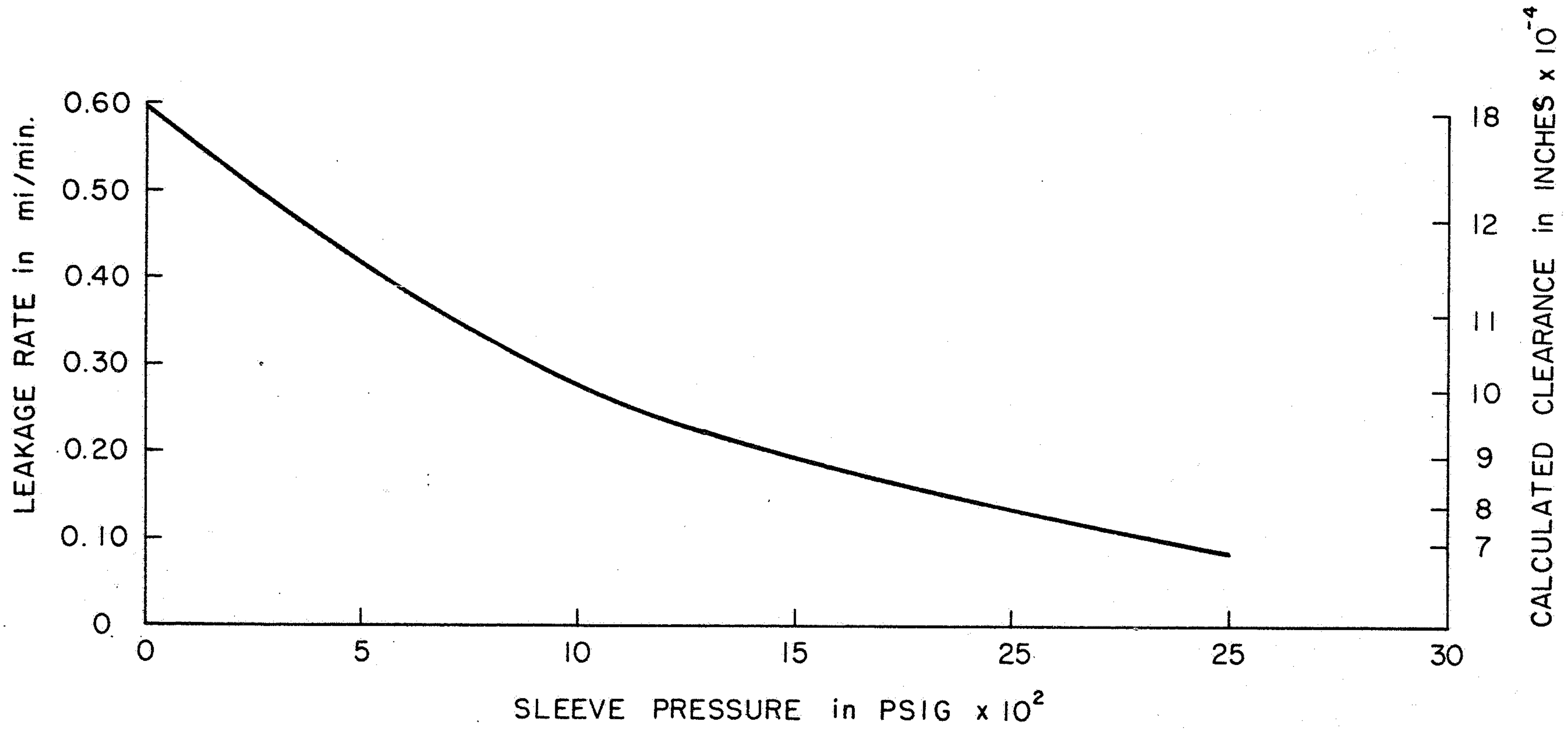


Figure 4.18 – LEAKAGE CALIBRATION OF VARIABLE CLEARANCE DEVICE.

3. Clearance-Actuating Force-Cleanliness Level - With the variable clearance device calibrated to clean oil conditions, the performance of the device measured when discrete cleanliness levels which were circulated through the fixture the non-generating stand. The actuating forces were measured at arbitrarily selected clearances with constant cleanliness levels. The resulting data is recorded in Tables 4-2, 4-3 and 4-4 and plotted in Fig. 4-19.

The data clearly validates the theorized approach to the referenced problem. Furthermore, along with the reported research accomplishment, a capability in general understanding of contamination tolerance, instrumentation, design and technique have developed to the predicted state of comprehension that will serve as a basis for important contributions that are requisite to advancing the state of the art.

By way of summary, the results of this research supports previous and new conclusions in respect to the concept of contamination tolerances for fluid power components. Conclusively, the sensitivity to contamination of the reported variable clearance spool valve device is at least a function of the following things:

1. Flow clearances
2. Components' material properties and surface finishes
3. Precision of manufacture
4. Contamination quantity and size distribution
5. Contamination physical properties
6. Fluid properties
7. Routine of operation, in terms of steady state time periods
8. Operating conditions - temperature and pressure.

TABLE 4-2

ACTUATING FORCE WITH CLEANLINESS LEVEL OF 29.48

Sleeve Pressure (Psig)	Clearance (Inches)	% of Maximum Actuating Force (%)
0	13×10^{-4}	60
1000	10×10^{-4}	65
1500	9×10^{-4}	65
2000	8×10^{-4}	100

TABLE 4-3

ACTUATING FORCE WITH CLEANLINESS LEVEL OF 30.48

Sleeve Pressure (Psig)	Clearance (Inches)	% of Maximum Actuating Force (%)
0	13×10^{-4}	40
1000	10×10^{-4}	50
1500	9×10^{-4}	100

TABLE 4-4

ACTUATING FORCE WITH CLEANLINESS LEVEL OF 31.48

Sleeve Pressure (Psig)	Clearance (Inches)	% of Maximum Actuating Force (%)
0	13×10^{-4}	45
1000	10×10^{-4}	60
1500	9×10^{-4}	100

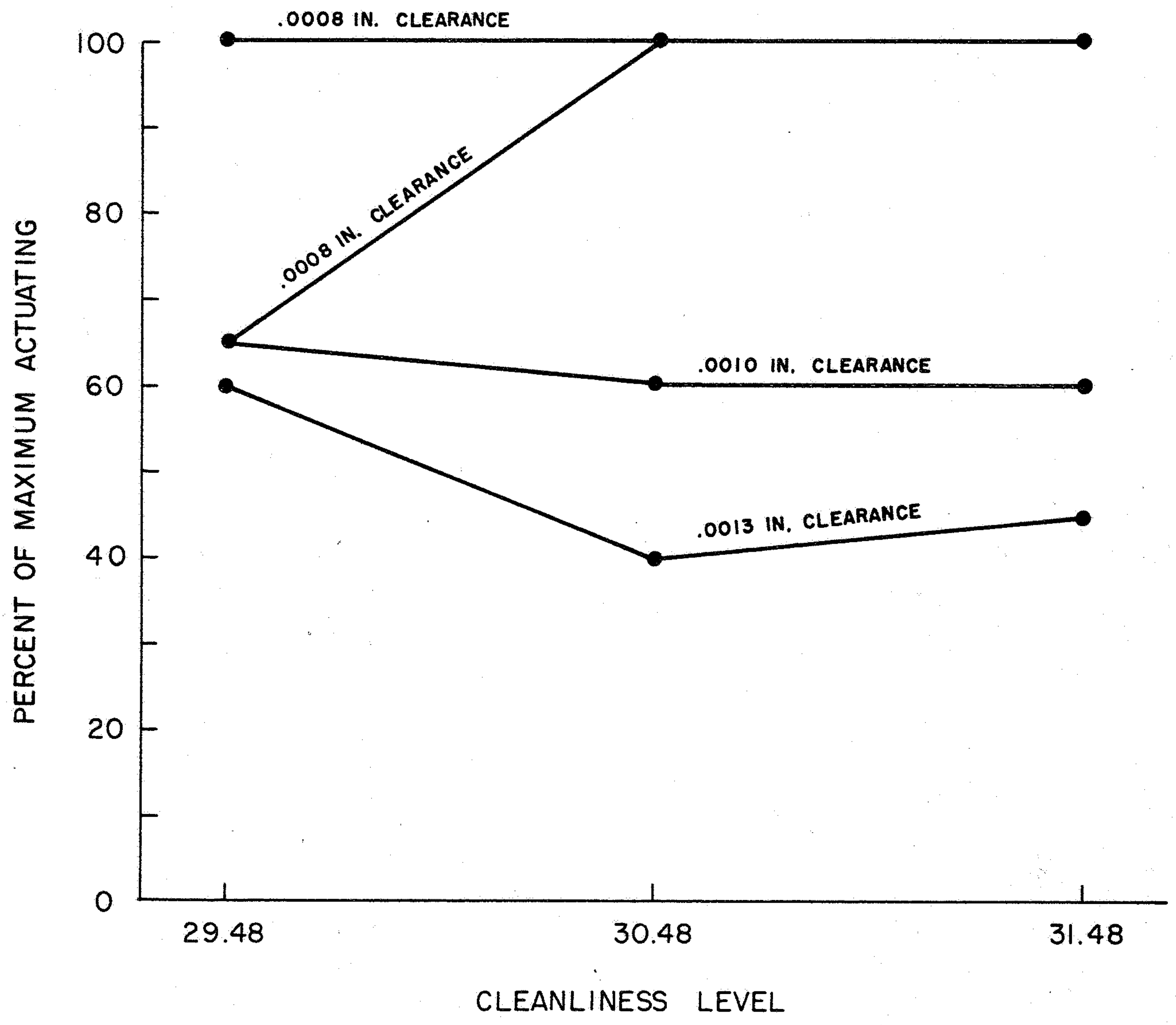


Figure 4.19 – CLEARANCE – ACTUATING FORCE – CLEANLINESS LEVEL RELATIONSHIP.

Some items in the above listing could be combined. For example, "Contamination quantity and size distribution" constitute a defined contamination level. However, the items are included in the expanded form to emphasize their individual importance to the overall scope of the research.

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APPENDICES

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APPENDIX A

DEFINITIONS

It is important for communication purposes to define the terms used in this report even though there may be considerable controversy if used out of context. The following terms and definitions have been accepted and used extensively by the Fluid Contamination Laboratory at Oklahoma State University and will be used in this report:

1. Contaminant Level - a quantitative expression for the size distribution, shape, quantity and physical properties of one type of particulate matter in a fluid.
2. Contamination Level - a quantitative expression for the size distribution, shape, quantity and lumped physical properties of a mixture of contaminants in a fluid. This is the general case.
3. Clean - a qualitative expression for an acceptable contamination level.
4. Particle Size Distribution - the cumulative frequency of occurence of each contaminant particle size in a fluid.
5. Gravimetric Level - the quantity of contamination by weight per standard specification.
6. Cleanliness Level - the degree of contamination based on a standard specification.

7. Contamination Tolerance Level - the contamination level which cannot be exceeded and still allow components to have a specified performance, reliability, and life expectance. Contaminant tolerance level would refer only to the influence of one type of contaminant.
8. Background Contamination Level - the contamination level achieved when a fluid has passed through the system's filter.
9. Environmental Contamination - that which enters the system through breathers and seals.
10. Generated Contamination - that which is generated within the system components as a result of such actions as wear, cavitation and erosion.
11. Built-in Contamination - that which exists within a system due to the processes used in manufacturing lines, components and fluid.

APPENDIX B

CLEANING FLUID SAMPLE CONTAINERS

The validity of the results from a contamination level analysis of a fluid sample is dependent as much upon the cleanliness level of the sample containers as upon the analysis techniques and the sampling method. The degree of cleanliness required for sample containers is directly associated with the contamination level of the fluid specimen; that is, heavily contaminated fluid does not require the use of ultraclean containers. However, since modern hydraulic system fluid must be maintained at relatively low contamination levels, it should be an established practice that extremely clean sample containers are used. In many cases (for hydraulic systems), the use of new or "surgically clean" bottles is inadequate. Bottles free from live microorganisms may contain a high level of organic and inorganic particulate matter. Since individual particles below 40 microns cannot be seen with the naked eye, the fact that material in not visable in a bottle is no assurance of its cleanliness.

The cleaning of any part depends not only upon the effective separation of particulate matter from the surfaces of the part, but also the cleanliness level of the rinsing fluid. Experimental studies have shown that an ultrasonic bath having a power level of at least 10 watts per square inch is needed to detach particulate matter from most surfaces under ordinary circumstances. The transmission of the ultrasonic waves is increased by the addition of detergents in the fluid and the use of detergents is also helpful to remove oil films from surfaces that are to be cleaned.

Clean room studies at Oklahoma State University for NASA have resulted in the establishment of specific procedures for cleaning fluid sample containers. The procedures outlined herein are the culmination of many tests and the degree of repeatability is excellent. Based upon the experience gained in using the procedures, they are recommended for all containers where hydraulic system fluid is sampled.

The cleaning process involves a procedure used outside the clean room for the initial preparation of the containers and a procedure used inside the clean room for the final preparation of the containers.

Initial Cleaning Procedure (In Clean Area)

1. Bottles and caps are placed in an ultrasonic cleaning bath. The bath is filled with warm water, and a high quality detergent (non-residue type) added. Run for approximately 15 minutes.

2. Drain ultrasonic bath and rinse free of cleaning solution with tap water.

3. Empty bottles and caps and rinse under faucet. Return bottles and caps for clean water rinse in the ultrasonic bath (approximately 15 minutes).

4. Drain ultrasonic bath, empty bottles, refill ultrasonic with clean water. Return bottles and caps for a second rinsing (approximately 10 minutes).

NOTE: This procedure is for new unused bottles. If bottles are dirty the washing process (Steps 1-4) should be repeated as many times as necessary.

5. Drain bottles and rinse with acetone using approximately 3-5 ml. depending upon the size of the bottle.

6. Place bottles in a 150°F oven until dry. Do not place caps in oven to dry.

7. Do not cap the bottles while hot as this will cause condensation in the bottles.

Final Cleaning Procedure (In Clean Room)

1. Each bottle is rinsed with approximately 3-5 ml of Isopropyl Alcohol which has been filtered through (.45 micron) Millipore pad. This is to assure the removal of any moisture that might have accumulated. Rinse the caps also.

2. Rinse each bottle and bottle cap twice with approximately 3-5 ml of ether (Skelly F) which has been triple-filtered through (.45 micron) Millipore pad.

3. Cut plastic squares (Polyethelyne Film) to fit over bottle neck. Rinse squares with filtered (.45 micron) ether and place over bottle opening, securing with a rubber band.

4. Cap bottles.

Experience is a very important teacher in regard to sample bottle washing. Great errors can be incurred through extremely subtle mistakes in the cleaning technique used. At OSU it is believed that the sample bottles used in important tests should only be used for sample taking. That is, they should not be used in extra curricular activities such as in contaminant capacity injection testing. Also, the bottles that are used for sampling are washed as soon as it is possible to complete the sample analyses. This reduces the chance of solid particles becoming "glued" to the bottle surface under a dry oil film.

APPENDIX C

SAMPLING TECHNIQUES FOR DYNAMIC FLUID SYSTEMS

The contamination level of a fluid system is a quantitative expression for the degree of cleanliness of the entire volume of fluid contained in the system. Since it is impossible in most instances to analyze 100% of the fluid, some means must be employed to extract a small sample which is representative of the entire volume and assume that it reflects the contamination level of the total quantity of fluid. Samples from the system can be obtained either statically, while the fluid is at rest, or dynamically, while the fluid is in motion. Static sampling, although it may be more convenient, gives erratic results in most instances. The contamination level of static samples varies with time, viscosity, surface tension, type of contaminant, vibration and location of extraction. The amplification of errors in static sampling prohibits the extrapolation to the entire volume and may lead to invalid conclusions. Dynamic sampling has the advantage that particulate matter entrained or moving with the fluid is represented in the pseudo-homogeneous sample as in the main stream. A sample properly removed from a dynamic system which has been allowed to circulate and mix for a suitable period of time, is more likely to be representative of the entire active fluid in the operating system.

There are essentially two types of dynamic sampling methods--isokinetic and turbulent. Isokinetic sampling requires the existence of laminar flow in the extraction section. The probe used to conduct the sample from the extraction section is critical from the standpoint of configuration and orientation. Anisokinetic conditions can result if the streamline velocity in the section is not equal to the velocity of the fluid in the probe. Under laboratory controlled conditions, isokinetic sampling is extremely accurate and can be used as a standard.

Since it is difficult to insure a true laminar flow condition in the "crooked" lines of most hydraulic systems, a practical substitute for the isokinetic sampler is the turbulent sampler. Turbulent flow, by definition, produces a violent mixing action and provides a uniform particulate distribution in the fluid. Several independent studies have shown that the quality of a sample is not necessarily dependent on the sampling flow rate or the probe configuration, if the fluid in the main stream is taken from a turbulent region. The results shown in Table C-1 are a representative comparison of particulate distributions obtained from the same flow stream by isokinetic and turbulent sampling methods. Based on over three years of work for NASA and the Air Force in fluid sampling at both laboratory and field levels, a practical technique has been developed by Oklahoma State University, which is being used in many areas of the Fluid Power Industry.

The OSU Field Sampling Method only requires a side tap in a turbulent section of the main line. An inexpensive sampling appendage such as shown in Fig. C-1 is used to extract the sample. The appendage consists of a quick-disconnect with dust caps, a ball valve and a hypodermic tube. The check valve part of the quick-disconnect and its mating dust cap are connected permanently to the side tap of the main stream. The non-check valve part of the quick-disconnect together with

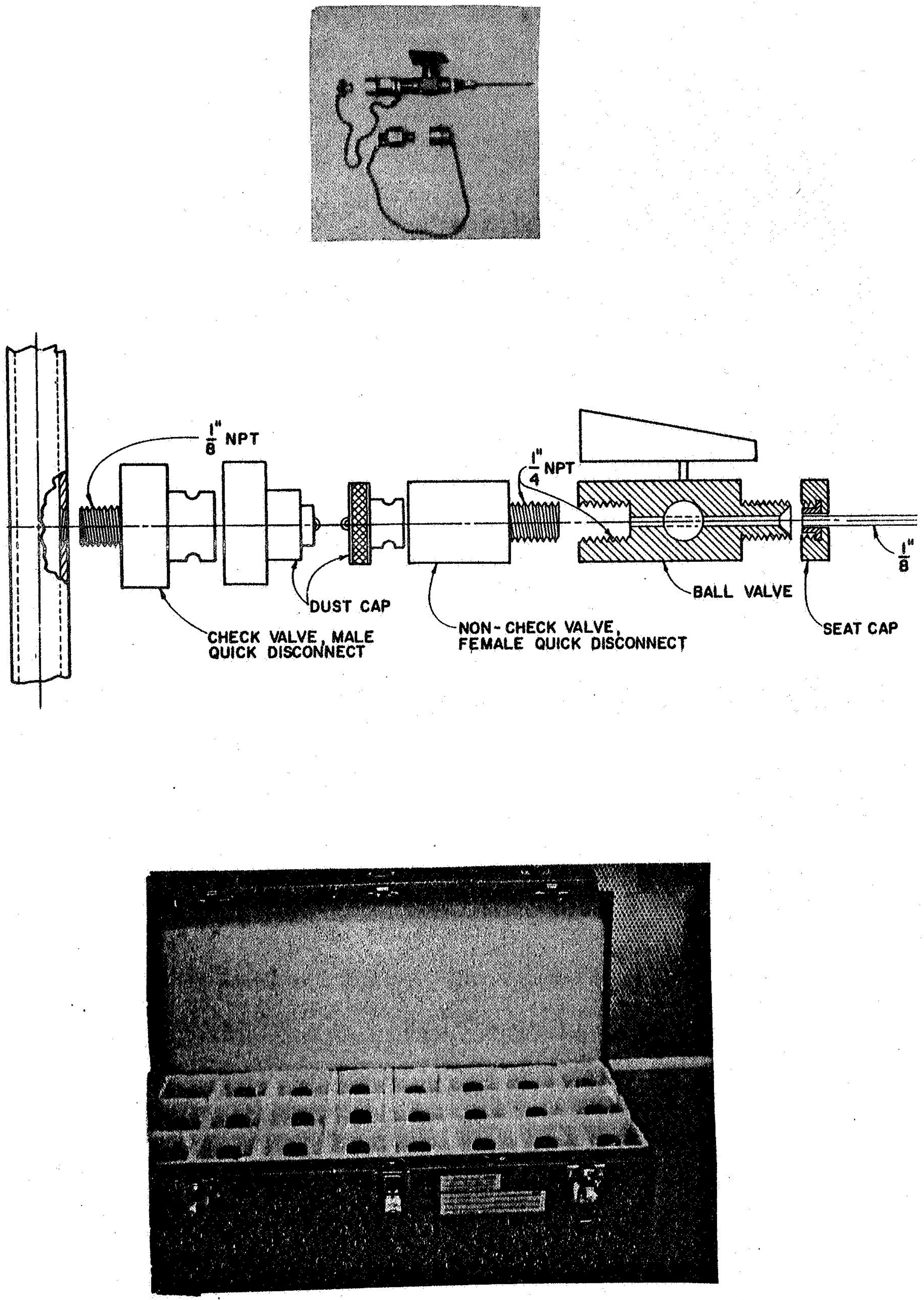

Figure C-1. Sampling Equipment

TABLE C-1

ISOKINETIC VERSUS TURBULENT SAMPLING

Particle Diameter	Particles Above	Specific Diameter
Microns	Isokinetic Sampler	Turbulent Sampler
	Test 1	
6	9115	9109
10	2007	1932
15	331	309
20	130	110
	Test 2	
6	10914	10792
10	2339	2590
15	350	492
20	117	198

its attached dust cap, ball valve and hypodermic needle, are used only when a sample is being extracted. A fully opened ball valve with a hypodermic type restriction is preferred over a partially open needle valve because a circular area provides the largest possible opening for a specific flow condition and minimizes "filtering" of the sample which occurs across partially opened needle valves. The length and size of the hypodermic tubing depends on the desired sample flow rate and the pressure in the main stream.

The sample valve assembly should be flushed with a "clean" solvent after the sample extraction operation to remove residual oil films. Prior to extracting a fluid sample, a volume of fluid should be flushed from the sample valve assembly equal to at least three times the internal volume of the entire appendage. A minimum of environmental exposure of the sample fluid is achieved by using the sample bottles sealed with a polyethelene film and having the hypodermic tubing pierce the film.

Of course, large volume samples are generally recognized for their enhancement of statistical accuracy. Just as surely the relative value of "large" is usually tempered by practical considerations.

APPENDIX D

PARTICLE COUNTER TESTS

The sizing and counting of particles to give a quantitative appraisal of the contamination level of a fluid has long been dominated by microscopic methods. These methods are reliable only when special, very stringent precautions are taken; however, they have a number of undesirable characteristics. The microscopic methods are time consuming, involve a high degree of personal judgment, and are difficult to reproduce.

During the past decade, the development of automatic particle counters and the need for processing a large number of samples have resulted in a general decline of microscopic analyses for contamination control purposes. The HIAC Particle Counter is one such counter that has become accepted by some for its high degree of repeatability and accuracy. This counter uses the light-blocking effect of a dynamic particle as a direct indication of its size. The particle is assigned a size value equal to the diameter of a circle whose projected area would block out an equal amount of light; hence, a 10 micron particle is one whose projected area is effectively equal to that of a circle 10 microns in diameter. The particular model used to evaluate the samples reported herein was a standard production model with provisions for a simultaneous monitoring of four particle size ranges.

Operation

The sample bottle containing the fluid specimen is connected directly to the microcell of the instrument by means of a sample bottle adapter. Air pressure is applied to the bottle, forcing the fluid through the microcell. The flow characteristics are such that each solid particle passes a sampling window in the cell in single file. A beam of light is collimated by the long window and directed through the fluid stream so as to impinge on a phototube on the opposite side. Whenever a foreign particle in the fluid stream passes the window, a portion of the light beam is interrupted. This creates a change in the output signal from the phototube which is proportional to the size of the particle passing the light beam. The signal change is amplified and sent to counter circuits that have been pre-adjusted by the operator to various sensitivities for simultaneous counting of individual size ranges. The particle count is cumulatively tallied with respect to calibration sizes. After passing the sampling window, the fluid is collected in a graduated cylinder so that results can be recorded in terms of particles in a given volume of fluid.

The counter can be calibrated by various calibration procedures suggested by the manufacturer. For the particular tests reported herein, a microscopic check was performed to set the counters.

Calibration

The counter was calibrated by means of a technique developed at OSU where a "standard" fluid contaminant mixture, which had been analyzed optically by means of an image splitter eye piece, was used. An adjustment is provided for each counter module so that the sensitivity may be calibrated as desired. Table D-1 lists the calibration settings for the HIAC counter used in the OSU Laboratory. These calibration settings apply only to the particular counter used in the OSU Laboratory.

TABLE D-1

CALIBRATION SETTINGS FOR THE HIAC COUNTER

Diameter (Microns)	Calibration Setting
10	16
15	25
20	38
25	52
30	64
35	95
40	115

The air pressure was set to give a microcell flow rate from the sample bottle of 30 drops per minute. The tests are normally performed on 3 to 5 milliliters of fluid. To calculate the count within the set ranges, the count of any particular set size is subtracted from the count of the next smaller set size. For example, if the counters show 1500 particles greater than 5 microns and 500 particles greater than 10 microns, the count for the 5 to 10 micron range is 1000 particles.

In order to test for the sensitivity of the calibration to various contaminant levels, a "standard" was created in which 1 mg of AC Fine was placed in 100 ml of 5606 and counted. The contaminated fluid was then diluted with an equal volume of triple-filtered (0.45) 5606 and counted. The results (Table D-2) show the close agreement with the distribution obtained optically for AC Fine. The excellent agreement at

TABLE D-2

COMPARISON OF OPTICAL AND HIAC COUNTS

Diameter (Microns)	Number of Particles Larger Than Indicated Size in a 3 ml Sample			
	10 mg/L Contaminant Level		5 mg/L Contaminant Level	
	Optical	HIAC	Optical	HIAC
10	4500	4252	2250	1920
15	1900	1873	950	974
20	870	805	435	422
25	450	465	225	228
30	258	274	129	153
35	150	128	75	61
40	88	88	44	43

the lower contaminant level indicates the insensitivity of the calibration settings to contaminant levels within the overall contaminant level limitations of the instrument.

APPENDIX E

GRAVIMETRIC CONTAMINATION LEVEL

The gravimetric analysis of fluid samples gives a quantitative value for the contamination level. Although no information is gained regarding the particle size distribution in the fluid by this method, it is invaluable in establishing the quantity of contaminant entrained in the fluid. Gravimetric levels permit an understandable but sometimes misused, cleanliness level criterion to be established for given systems such as

1.	0 - 5 mg/l	ultraclean
2.	5 - 10	very clean
3.	10 - 20	clean
4.	20 - 40	questionable
5.	40 - 80	dirty
6.	80 -	very dirty

The gravimetric tests performed on the reported samples were conducted in accordance with SAE ARP-598 with certain modifications to y yield a technique which gives consistent results with different personnel. The procedure involves two phases:

1. Blank Control Analysis
2. Contaminant Analysis.

In order to effectively appraise the results of a gravimetric analysis some understanding of the procedure is necessary. A concise description is presented for this purpose.

Blank Control Analysis

The blank control analysis is required for each type oil sample in order to obtain the weight per unit volume that a non-contaminated sample would produce. Since a certain amount of the fluid would be retained in the filterdisc, this tare value is used as a basis for contamination level determination. The procedure is as follows:

1. A specific micron rated, 47 mm filter disc is placed in a clean petri dish and heated in an oven at 80°C for 15 minutes.
2. The petri dish and disc are then inserted in a desiccator for five minutes or until they are at room temperature.
3. Using forceps, the disc is removed from the petri dish and weighed on an analytical balance to the nearest .01 mg.
4. A sample of the fluid to be tested is triple-filtered through a 0.45 micron filter.
5. Twenty-five milliliters of the triple-filtered fluid is then passed through the prepared filter disc.
6. In addition to the filtered fluid, 100 ml of 0.45 micron triple-filtered petrileum ether is passed through the disc and finally the inside of the separatory funnel is rinsed with 50 ml of the filtered ether.
7. While still applying vacuum, the separatory funnel is removed and the disc is carefully washed toward the center with a wash bottle containing triple-filtered petroleum ether.
8. After the vacuum is released, the filter disc is removed with forceps and placed in a petri dish and in an 80°C oven for 15 minutes.
9. The petri dish and disc is then de-ionized to remove static electricity and placed in a desiccator for 5 minutes.
10. The disc is finally removed from the petri dish by forceps and weighed on an analytical balance.
11. Subtracting the original weight of the disc from the weight of the fluid processed disc gives the tare weight.

Contamination Analysis

The contamination analysis is conducted in approximately the same manner as the blank control analysis except that the fluid sample is the test specimen. The fluid being appraised for contamination level is shaken thoroughly in its receiving container. A sample volume of 100 ml is used for the test. The difference between the final weight of the disc and the weight of the initially cleaned disc is the contamination analysis weight.

Results

The actual weight of the contaminant per 100 ml of the test fluid is the difference between the Contamination Analysis Weight and the Blank Analysis Weight or tare. Normally, the results of a gravimetric test is reported in terms of mg/liter; therefore, the weight given above must be multiplied by ten.