A FUNDAMENTAL METHOD FOR EVALUATING FILTER PERFORMANCE FACTORS

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1961

Submitted to the Faculty of the
Graduate College of the
Oklahoma State University
in partial fulfillment of
the requirements for
the Degree of
MASTER OF SCIENCE
July, 1970

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FILTER PERFORMANCE FACTORS

Thesis Approved:

Thesis Adviser

Dean of the Graduate College

PREFACE

This thesis is concerned with methods for the evaluation of filter performance factors. The subject of filtration performance in fluid power systems is highly controversial and it is difficult to achieve industrial sanction of new concepts. The single pass filtration performance test for evaluating filter performance factors has gained wide acceptance by industry as a valuable technique. This filtration performance test is basically an outgrowth of previous developments in contamination control at Oklahoma State University. The final breakthrough which made this evaluation method feasible came as a result of the development of control concepts for each critical aspect of the testing method.

It gives me great pleasure to acknowledge my indebtedness to Dr. E. C. Fitch, Jr. for guidance, inspiration, encouragement, and support during my undergraduate and graduate endeavors.

In addition, I would like to express my appreciation to my colleagues, Earl Maroney and Leonard Bensch, for their constructive comments.

Miss Velda Davis for her help in preparation and submission of this thesis.

Most of all, I thank my wife, Barbara, and my two sons, Michael and Douglas, for their sacrifice, understanding and encouragement.

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CHAPTER I

INTRODUCTION

The development in recent years of complex, high performance fluid control systems has resulted in components which utilize extremely small orifices and clearance spaces. The users of these fluid control systems demand component reliability and life comparable with other components which make up the total machine. It is well known that the presence of solid particles in such components may result in malfunctions, excessive wear and/or degradation of static and dynamic performance. This means that the presence of solid particles will reduce both reliability and life of a fluid component. Previous studies have established that the amount of reduction in reliability and life of a fluid component is a function of the size distribution and concentration of particulate matter. The problem of matching the contamination level of the system fluid to the contaminant tolerance of the system components falls into the realm of contamination control.

One of the definitions for the word "control" is to check, regulate, or to keep within limits. Obviously, if control is to be exercised over the contamination in the system fluid, some quantitative limits must be established

to assess conformation. In order to develop a criterion for the proper system contamination level, the effects of various contamination levels on the performance, reliability, and life of system components must be known. Figure 1 illustrates a contaminant tolerance profile of a component that can be utilized to establish the maximum allowable system contamination level. Once the maximum allowable system contamination level is defined, the problem of contamination control becomes one of selecting or designing a filtration system capable of maintaining the fluid contamination level at or below the maximum allowable.

Many fluid control systems currently utilize components with low contaminant tolerances. Utilization of such components necessitates the use of filter elements exhibiting the capability of maintaining a very low contamination level. The search for better filter elements has led to the consideration of many different designs utilizing media such as paper, sintered metal powder, sinter metal fiber, and woven wire cloth. The criterion for selecting one design or medium over another is often based on qualitative information rather than fundamental knowledge of what contribution the filter element is capable of making to the system. Often, this approach has been forced on the designer because applicable filter design information has either been of a vague, empirical nature, or totally lacking.

In order to be sufficiently armed in his search for the most optimal filter, the system designer must have at his

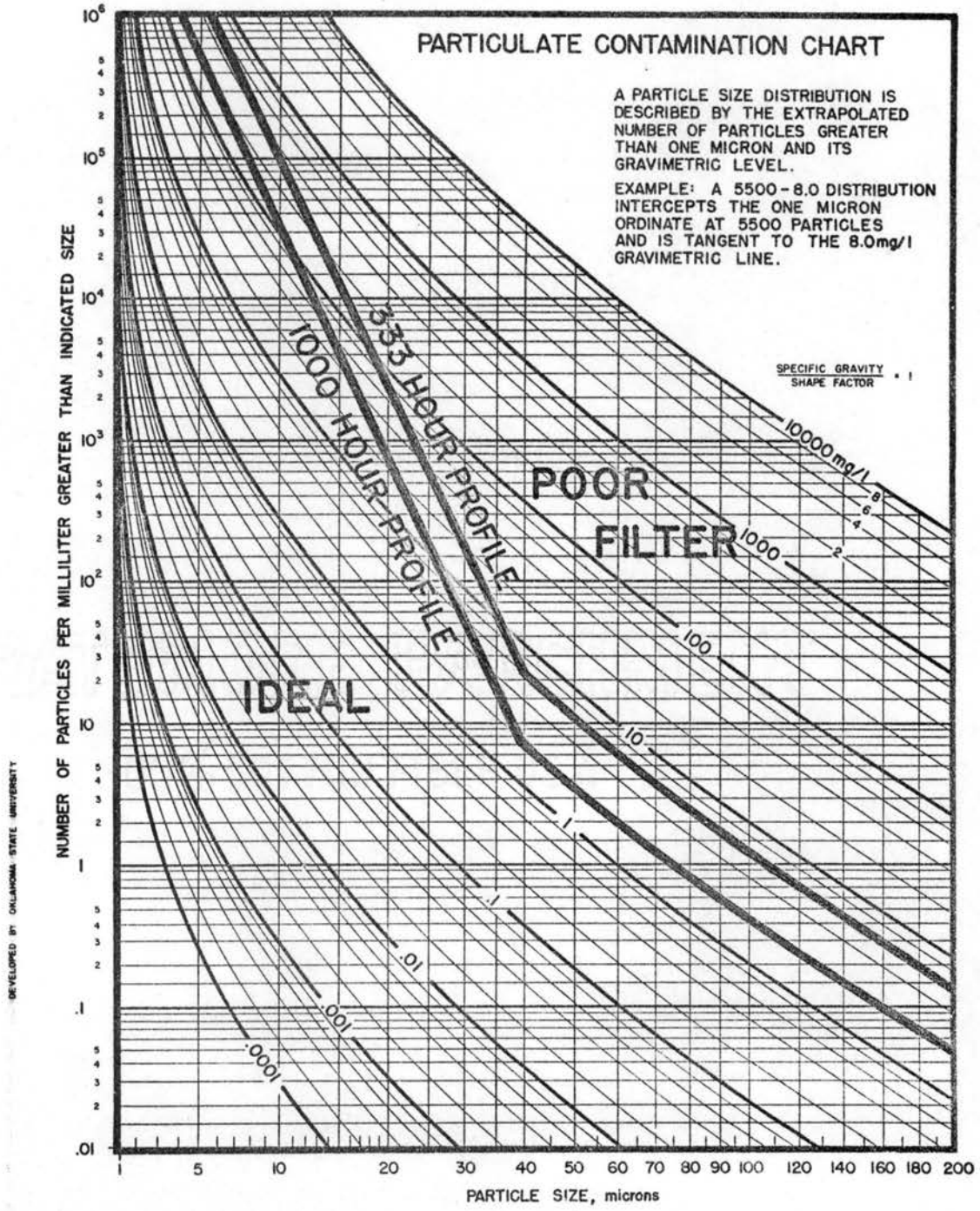


Figure 1. Component Contaminant Tolerance Profile

disposal comprehensive information about filter performance. Without this information, filter selection becomes a trial-and-error procedure. If a designer has good information concerning the efficiency, contaminant capacity, and the pressure-flow characteristics of the filter, he can generally make a comparative appraisal. Or better still, if the designer had good information concerning the contamination level which a filter is capable of maintaining in a system as well as the contaminant capacity and the pressure-flow characteristic, he can make an intelligent selection.

Many tests have been developed in the past to measure various filter parameters and their laboratory performance. In practically every case, these tests failed to produce information useful in selecting a filter for a particular application. Therefore, a new test was conceived at Oklahoma State University. This test, called a single-pass filtration performance test, possesses the necessary features to determine all critical filter performance factors and presents them in a usable manner.

This study will present and evaluate methods used in the past to reveal the performance of a filter. In addition, it will develop the control concepts needed to implement the single-pass performance test and establish a rigorous test method. Finally, it will be shown that the fully implemented single-pass filtration performance test is repeatable and that the generated information is unique to a specific filter.

CHAPTER II

PREVIOUS INVESTIGATION

Introduction

A filter has three factors upon which its performance is appraised:

1. Pressure drop for a given flow rate.
2. Contaminant holding capacity.
3. Contaminant distribution rating.

Historically, filter investigators have taken one of two "paths" in attempting to define these performance factors. One path led to a mathematical model by which one could solve for these performance factors given some information concerning the basic filter parameters. The other path led to empirical methods by which the three performance factors could be determined directly for a given filter.

Mathematical Model

The two important functions of a filter are diametrically opposed to one another. A filter is required to provide maximum restriction to the passage of particulate contamination while offering minimum resistance to the flow of system fluid. Therefore, most filter investigators

attempting to model the performance of a filter have been forced to consider the flow and filtration characteristics individually (1)-(13).

Flow Performance

It has been generally accepted that the capillary flow equation proposed by the French engineer, Henri Darcy, in 1856 can be utilized to describe the flow performance of a filter (1)-(8). Darcy's equation can be written in the following form:

$$V = \frac{k}{\mu} \frac{dP}{dL}$$

where:

- V is the fluid velocity in the capillary.
- μ is the dynamic viscosity of the fluid.
- $\frac{dP}{dL}$ is the pressure gradient in the medium.
- k is a proportionality constant, defined as permeability.

Filter studies concerned with flow performance have established various expressions for the proportionality constant involved in Darcy's equation. These expressions for permeability have attempted to relate the filter parameters to specific flow performance. For example, Kozeny (1) and Carman (2) both made contributions to the definition of permeability. Utilizing some of Kozeny's work, Green and Durvez (3) attempted to define the pressure gradient. Grace (4), Seed and Foule (5), and Cranston (6) all worked

from the Hagen-Poiseuille form of Darcy's equation by introducing such factors as porosity as basic filter parameters.

Fitch (7) started with the basic force balance relationship on the fluid within the medium and proceeded to the equation:

$$V = \left(\frac{\varphi d_a^2}{32\tau}\right) \frac{1}{\mu} \frac{dP}{dL}$$

where:

d_a is the equivalent cylindrical diamter of the capillaries.

Tucker (8) utilized Fitch's work and was able to experimentally verify this model for wire cloth media where the tortuosity τ is equal to one. Although Tucker was able to prove the validity of this flow performance model for surface media, later attempts to extend it to depth media without considering a value for the tortuosity effect did not meet with as much success.

Filtration Performance

Although it is generally recognized that there are three basic mechanisms by which a filter media removes contaminant - adsorption, absorption, and mechanical filtration - the majority of the research on filter media for fluid power applications has only considered mechanical filtration. Mechanical filtration is accomplished by direct

interception of particulate contaminant in the interstices of the filter medium.

The mechanisms of mechanical filtration have received the the attention of several investigators, including Herman and Bredee (9), Gonsalves (10), Grace (4), and Stone (11). Collectively, they establish four of these mechanisms:

(1) Complete Blocking occurs when the individual particles are large enough to plug the filter pores.

(2) Standard Blocking occurs when particulate contaminant adheres to the filter medium.

(3) Cake Filtration occurs when solid particles retained at the surface of the filter build up to form a porous cake.

(4) Intermediate Blocking is lossely defined as a filtration mode between standard blocking and cake filtration.

Herman and Bredee suggested that these four mechanisms could be utilized to determine the value of an exponent in a proposed filtration rate equation. This suggestion was investigated and abandoned by Stone since he established that more than one of these mechanisms could occur simultaneously.

Cranston (6), on the other hand, assumed a complete blocking mode and suggested a filtration performance model based on the pore size distribution of the filter media. He further assumed that the pore size distribution and the capillary size distribution were essentially equal.

Cranston concluded that the capillary size distribution could best be established by performing an efficiency test in which the particle size distribution of both the feed and the filtrate were measured as shown in Figure 2. The efficiency information was utilized to produce a graph of transmission factor versus particle size, Figure 3. Cranston showed that the characteristic shape of the capillary size distribution can be obtained by measuring the slope of the transmission curve at various particle sizes.

Ludwig (12) and Casaleggi et al. (13) conducted experiments on surface-type filter media which, with some slight modifications, validated Cranston's theory. Tucker showed that Cranston's capillary size distribution curves were valid and could be described by a Gaussian or normal distribution function for wire cloth.

Summary of Mathematical Modeling

Mathematical modeling techniques have been very successful in describing both the flow performance and filtration performance of simple surface-type media. These techniques have not worked well for complex depth-type media. Also, there is one performance factor which has not been considered in the mathematical modeling approach and that is the contaminant holding capacity of filter media. This factor is very important in determining the filter change period which must be utilized in field service. Furthermore, a designer would have difficulty in predicting

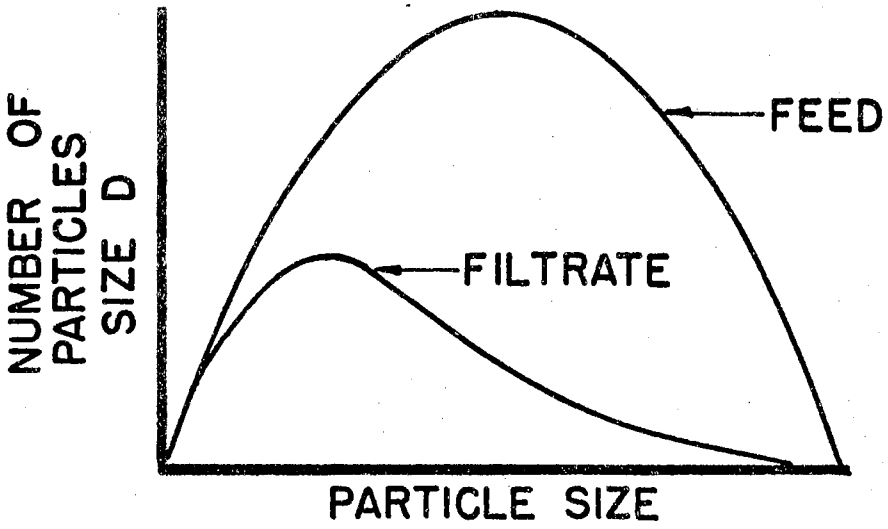


Figure 2. Particle Size Distribution Curve From an Efficiency Test

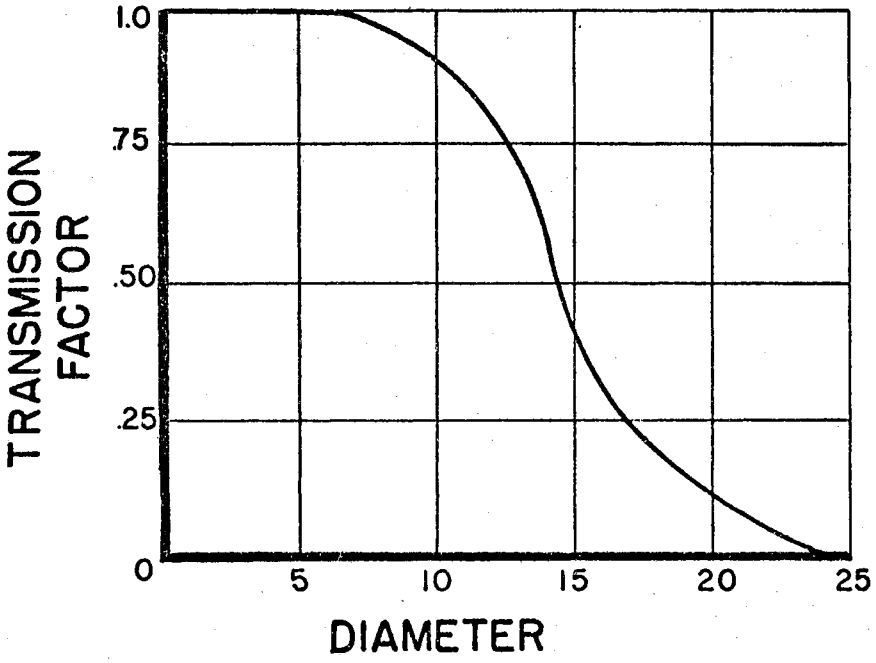


Figure 3. Typical Transmission Curve

the capability of a filter to maintain a given contaminant level in an operating system from any of the filtration performance models that have been suggested.

Filter Ratings

Because of the poor correlation experienced between laboratory and field results of filtration performance, investigators have established arbitrary rating methods. The most common expressions for describing a filter medium are nominal rating or absolute rating. The definitions of these terms, according to SAE AIR 887, are as follows:

(1) Nominal Rating - is "a measure of the removal of a given percentage by size of a given artificial contaminant above a certain size with the element heavily loaded at rated flow." "Nominal ratings often become mere names or code identification for filters; and since existing Military specifications do not specify nominal filter size, further use of this term to describe a filter performance should be discouraged."

(2) Absolute Rating - "is defined as the largest size hard spherical particle which will pass through the filter element." "It must be recognized that some non-spherical particles larger than the absolute rating of the filter will be able to pass through the filter."

These two rating methods give no information concerning the three performance factors upon which a filter's capability is evaluated. In other words, the absolute or nominal rating of a filter does not indicate the pressure-flow characteristic, the contaminant holding capacity, nor the contaminant distribution rating.

Filtration Performance Tests

Realizing the importance to a fluid power system designer of having comprehensive information concerning filter performance available, some filter investigators approached the problem from an empirical standpoint. These empirical test methods were initiated to determine the three filter performance factors directly.

In 1963, a program was established at Oklahoma State University to develop a test procedure which would determine the contaminant capacity and particle size efficiency of a filter element simultaneously. The contaminant capacity was established by injecting accurately weighed contaminant slurry into the flowstream of the filter element being tested and recording the subsequent pressure rise up to a predetermined pressure differential. The particle size efficiencies were determined by sampling upstream and downstream of the filter element during the contaminant injection period. These samples were analyzed in a clean room utilizing an automatic particle counter to determine the

number of particles present in the samples in four particle size ranges.

The results of the contaminant capacity tests were generally satisfactory; however, the results of the efficiency analysis were very erratic. This was due to insufficient control of both the filter testing procedures and the clean room particle count analysis. In light of this, the program was temporarily abandoned.

By 1968, work on the NASA Filtration Mechanics Program led to better testing control and a program was again initiated at Oklahoma State University to develop testing procedures to determine contaminant capacity and multiple efficiencies of a filter element (14). This was the beginning of the flowing single-pass filtration performance test as it is conducted today. The initial results of this program indicated that better control had indeed been developed, particularly in the particle count analysis area. However, the efficiency results were still somewhat erratic, indicating insufficient testing procedural control.

During the summer of 1968, Dr. E. C. Fitch, who had directed the two previous programs, recognized that the results of these programs indicated a unique downstream particle size distribution for each filter element tested. He reasoned that if sufficient control could be attained with this type of test, all three of the critical filter performance factors could be evaluated. In other words, if the injection procedure could be controlled sufficiently to

produce a predetermined constant upstream contaminant environment and the sampling and sample analysis techniques could be sufficiently controlled to produce consistent results, then a unique contaminant distribution rating could be established for a given filter. This would make the test complete, since both the flow-pressure characteristics and the contaminant holding capacity of a filter were already satisfactorily determined.

In the fall of 1968, a program was initiated under the direction of the author to develop the control necessary to make the single-pass filtration performance test capable of evaluating the three performance factors. In the following chapter, the development of the control concepts necessary to implement the single-pass test will be outlined in detail.

CHAPTER III

SINGLE-PASS FILTRATION PERFORMANCE TEST

Introduction

The single-pass filtration performance test was developed more from a fluid power user's standpoint than from the point of view of filter manufacturers. However, it was reasoned that a method which could satisfy the needs of the user should be very beneficial to a progressive filter manufacturer. It was assumed that if the fluid power designer was able to rigorously define his filtration needs, the knowledgeable filter manufacturer could and would provide a filter element to satisfy the requirements.

Specifying the requirements of a filter element by some arbitrary absolute or nominal rating does not reveal the desired filter performance factors. The designer of a fluid power system cannot relate the performance of a filter element acquired by such ill-defined standards with the specific requirements of his system. The single-pass performance test is designed to provide information which can rate a filter according to its capability to maintain a prescribed contamination level in an active hydraulic system. This performance test also reflects the over-all performance characteristics of a filter element as exhibited by its

separation efficiency, contaminant capacity and pressure-flow relations.

The importance of measuring the separation efficiency, contaminant capacity and pressure-flow characteristics becomes apparent when the pore structure of a filter medium is considered. The pore structure establishes the filter element's ability to achieve and maintain a given contamination level for a specific length of time at a given pressure loss. The structural integrity and tortuosity of the medium establishes whether an element will exhibit a significant change in separation efficiency as it continues to trap contaminant and experiences an increase in pressure differential. It is not uncommon for particular filter elements to display severe degradadation in efficiency when the differential pressure begins to rise. Such a drop in efficiency can mean that the filter element is unloading, which accounts for noticeable increases in contamination levels exhibited in some systems.

Concept of Single-Pass Filtration Performance Testing

The contamination level in a flowing system is dynamic in nature. That is to say that the contamination level of a system varies at every point in the system. This can best be illustrated by the block diagram shown in Figure 4.

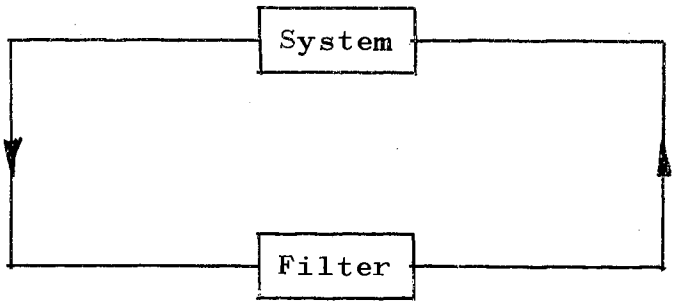


Figure 4. Block Diagram of Dynamic System

The components making up the block labeled "system" add contaminant to the system fluid by allowing contaminant to enter from external sources, by generating contaminant as they operate, or both. Therefore, the contamination level of the fluid upstream of the filter is a function of the contamination level that the filter is capable of producing and the contamination ingression. Thus, if a filter is capable of removing the contamination added by the system, the contamination level upstream from the filter will be a function of the generation and ingression rates.

The single-pass filtration performance test must duplicate the upstream environment found in an active system. In considering the contaminant environment in which a filter should be tested to provide a realistic test, the amount of ingression and generation must be established. Many mobile equipment manufacturers have reported that "handfuls" of contaminant enter their systems from external sources. Others have measured "many grams" of contaminant entering

from ingression. Since one teaspoon (20.8 grams) of contaminant in a 55 gallon fluid system represents a gravimetric level of 100 mg/liter, a value of 75 mg/liter or even 100 mg/liter as an upstream test environment for a filter is realistic.

In order to achieve the necessary control to implement the single-pass performance test, each critical aspect of the testing procedure and fluid analysis must be thoroughly investigated. The critical aspects that must be controlled are:

(1) contaminant,
(2) contaminant preparation,
(3) contaminant injection,
(4) sampling,
(5) background contamination level,
(6) test filter inspection,
(7) sample bottle preparation,
(8) fluid flow,
(9) pressure differential measurements,
(10) sample analysis, and
(11) test sequence.

Since the success of the single-pass filtration performance depends upon establishing control in each of these critical aspects, the requirements of each must be fully defined.

Contaminant Requirements

To obtain satisfactory results from any filtration performance test, the selection of the contaminant becomes of paramount importance. A test contaminant must possess properties similar to those of a contaminant encountered in a fluid power system operating in field service. It must be compatible with the contaminant utilized in other contamination control work if any correlation is to be realized. Accurate information must be available concerning its distribution and the consistency of this distribution. And certainly it must be universally available to anyone wishing to conduct a similar test. Finally, a usable test contaminant must be accepted by industry as an artificial contaminant.

Requirements for Contaminant Preparation

The preparation of the contaminant will determine whether the contaminant environment that is established will be repeatable, consistent, and known. Injection of a contaminant in a dry form results in an inconsistent and erratic contamination level mainly due to inability to precisely meter dry contaminant. Thus, in order to accurately control the rate of injection of contaminant, it must be prepared in a form which is readily meterable. In light of this and previous experience, a contaminant slurry becomes very attractive. Care must be taken, however, in the preperation of this slurry to see that the contaminant is

thoroughly dispersed and completely oil-wetted prior to injection.

Requirement for Contaminant Injection

Obviously, the injection of contaminant must be precisely controlled if a known, constant contamination level is to be created. Assuming that the contaminant can be metered accurately, a material balance relationship must be developed for the injection system. Further assuming that the contaminant will be placed in an injection chamber and introduced as a step input, the controlled contaminant ingression rate can be expressed in terms of the amount of contaminant added per unit time. This expression can be written as

$$R_c = \frac{W_c}{T_i} \text{ (gm/min)}$$

where:

R_c = contaminant ingression rate (gm/min).

W_c = weight of contaminant in injection chamber.

T_i = time to displace injection chamber volume.

Based upon flow rate considerations, the time to displace the injection chamber volume is

$$T_i = \frac{V_i}{Q_i}\left(\frac{\text{Gal}}{\text{Gal/Min}}\right) = \frac{V_i}{Q_i} \text{ (min)}$$

where:

V_i = injection chamber volume

Q_i = injection flow rate.

Substituting the relation for T_i into the equation for contaminant ingression rate yields

$$R_c = \frac{W_c}{V_i} Q_i \left(\frac{gm}{gal} \frac{gal}{min}\right) = \frac{W_c}{V_i} Q_i \ (gm/min).$$

The gravimetric contamination level of the fluid entering the test filter is described by

$$G = \frac{R_c}{Q_f} \left(\frac{gm/min}{gal/min}\right) = \frac{R_c}{Q_f} \ (gm/gal)$$

where:

Q_f = rated filter flow.

Substituting into this equation, the relationship developed for R_c and converting to standard gravimetric units gives

$$G = \frac{W_c}{V_i} \frac{Q_i}{Q_f} \left(\frac{gm}{gal} \frac{gpm}{gpm}\right) \left(\frac{1000 \ mg/gm}{3.785 \ liter/gal}\right)$$

$$G = 264 \frac{W_c}{V_i} \frac{Q_i}{Q_f} \ (mg/liter).$$

This gravimetric expression can be restated as the injection flow rate by

$$Q_i = \frac{1}{264} \frac{V_i}{W_c} \frac{Q_f}{G}.$$

Since the volume of the injection chamber and the gravimetric contamination level are know or specified, the

injection flow rate equation becomes

$$Q_i = K \frac{Q_f}{W_o}.$$

If the volume of the injection chamber is taken as .176 gallons and the gravimetric contamination level is 75 mg/liter, then

$$K = .05.$$

Figure 5 graphically illustrates the relationship of injection flow rate Q_i, rated filter flow Q_f, weight of contaminant added W_o, and the resulting displacement time T_i.

Requirements for Sampling

Since it is impossible to analyze 100% of the fluid flowing in the test system and a specified contamination level can only be maintained for a finite period of time, some means must be employed to extract a small representative of the flowing fluid. Samples obtained from the test system for the purpose of analyzing the contaminant level must be extracted dynamically from the system.

Fluid samples must be taken both upstream of the test filter and downstream of the test filter. The upstream sample can be analyzed to determine the exact contamination level established while the downstream sample analysis will indicate the capability of the filter. The extraction of these samples must be timed with the injection period to produce the desired results.

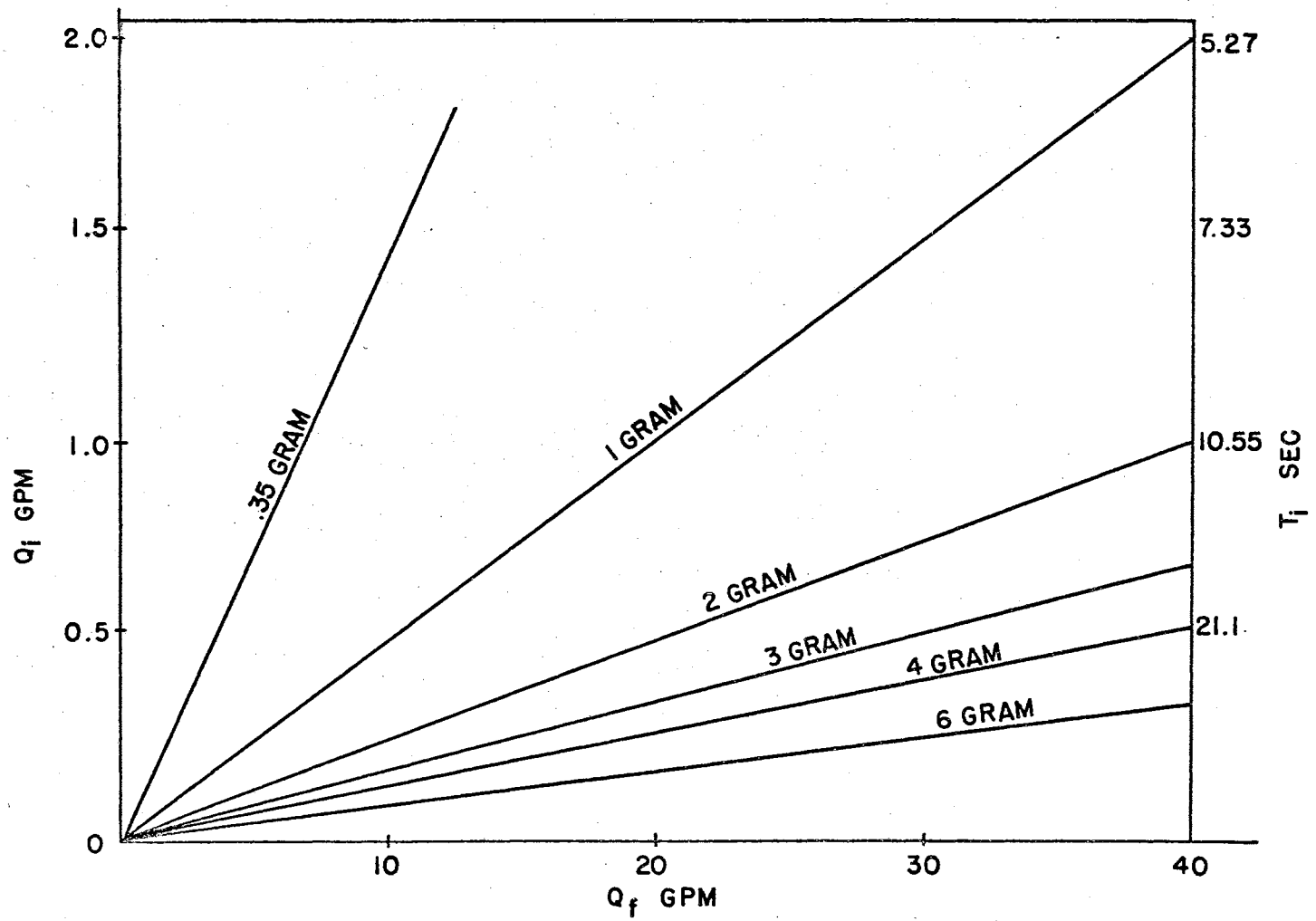


Figure 5. Injection Flow Rate Graph

In order to understand the importance of the sample period and duration, consider the injection cycle associated with the test. As the injection is started, the contamination level of the main flow stream rises to some maximum value. The contamination level is maintained for a period of time and then declines as the contaminant is flushed from the injection chamber. Samples taken only for the duration of injection cycle will tend to produce an average contamination level. This injection cycle is illustrated in Figure 6.

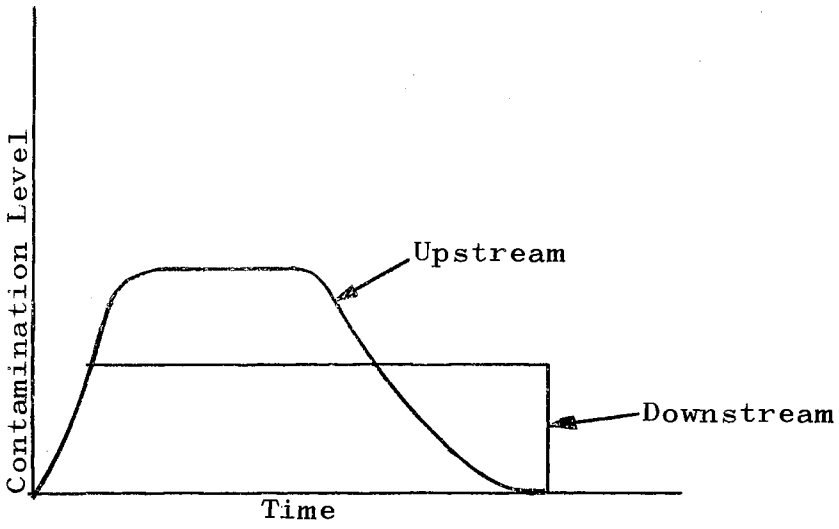


Figure 6. Injection Cycle

It is obvious that a sampling period precisely timed to agree with the injection interval as shown in Figure 6 is highly ideal and very difficult if not impossible to achieve.

The answer to this problem is to include the injection interval within the sampling period and consider the fluid extracted before and after the contaminant injection as dilution fluid. The dilution factor which must be applied to the sample analysis is described by

$$D.F. = \frac{T_s}{T_i}$$

where:

D.F. = Dilution Factor

T_i = time to displace injection chamber volume

T_s = sample time.

Requirements for Background Contamination Level

The requirements that must be placed on the background contamination level stem from two major considerations. First, if the material balance relationship derived for the contaminant injection is to produce the desired results, the background contamination level must be low enough to be considered negligible. Secondly, the dilution fluid introduced during sampling must be maintained at a very low (negligible) contamination level so as not to materially influence the contamination level of the samples.

Obviously, if the filter element being tested removes any contaminant, the downstream contamination level will be less than the upstream. Therefore, the effect of the background contamination level of the dilution fluid in the downstream sample will be greater than its effect on the

upstream sample. If the effect of adding this dilution fluid to the downstream sample is to be one per cent or less, the number of particles introduced by the background in the dilution fluid must be two decades below the number of particles present in the downstream fluid. In other words, if there were 1000 particles per ml greater than some given particle size in the downstream fluid, the background in the dilution fluid must not contain more than 10 particle per milliliter greater than that size particle if the resulting error is to be less than one per cent.

Requirements of Test Filter Inspection

If the results of a single-pass filtration performance test are to be considered a valid measure of a filter element's ability to remove and hold contaminant, the structural integrity of the element must be assured. Many times manufacturing defects will show up in the structure of a filter element. Defective end-cap and seam seals may lead to erroneous conclusions about the performance of an otherwise outstanding filter element. Damage to an element during shipping can produce the same erroneous results as end-cap and seam seal defects. Thus, requirements must be placed on a filter element regarding defective sealing surfaces and shipping damage.

Requirements of Sample Bottles

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 container as upon the analysis technique and the sampling method. The degree of cleanliness required for sample bottles is directly associated with the contamination level of the fluid specimen; that is, heavily contaminated fluid does not require the use of ultra-clean sample containers. However, since some of the filter elements being manufactured currently are capable of producing very low contamination levels, rigid control of sample bottle cleanliness must be a requirement of single-pass filtration performance testing.

In the case of sample bottles, the use of new or "surgically clean" bottles is inadequate. Surgically clean refers to the fact that the bottle does not contain any live micro-organisms. Bottles free from these live micro-organisms may contain a high level of organic and inorganic particulate matter. Since individual particles below 40 microns in diameter cannot be normally seen with the naked eye, the fact that material is not visable in a bottle is no assurance of its cleanliness.

The cleanliness level of sample bottles is generally expressed in classes. Figure 7 illustrates the cleanliness classes established for sample bottles. As was the case with the background contamination level, the cleanliness

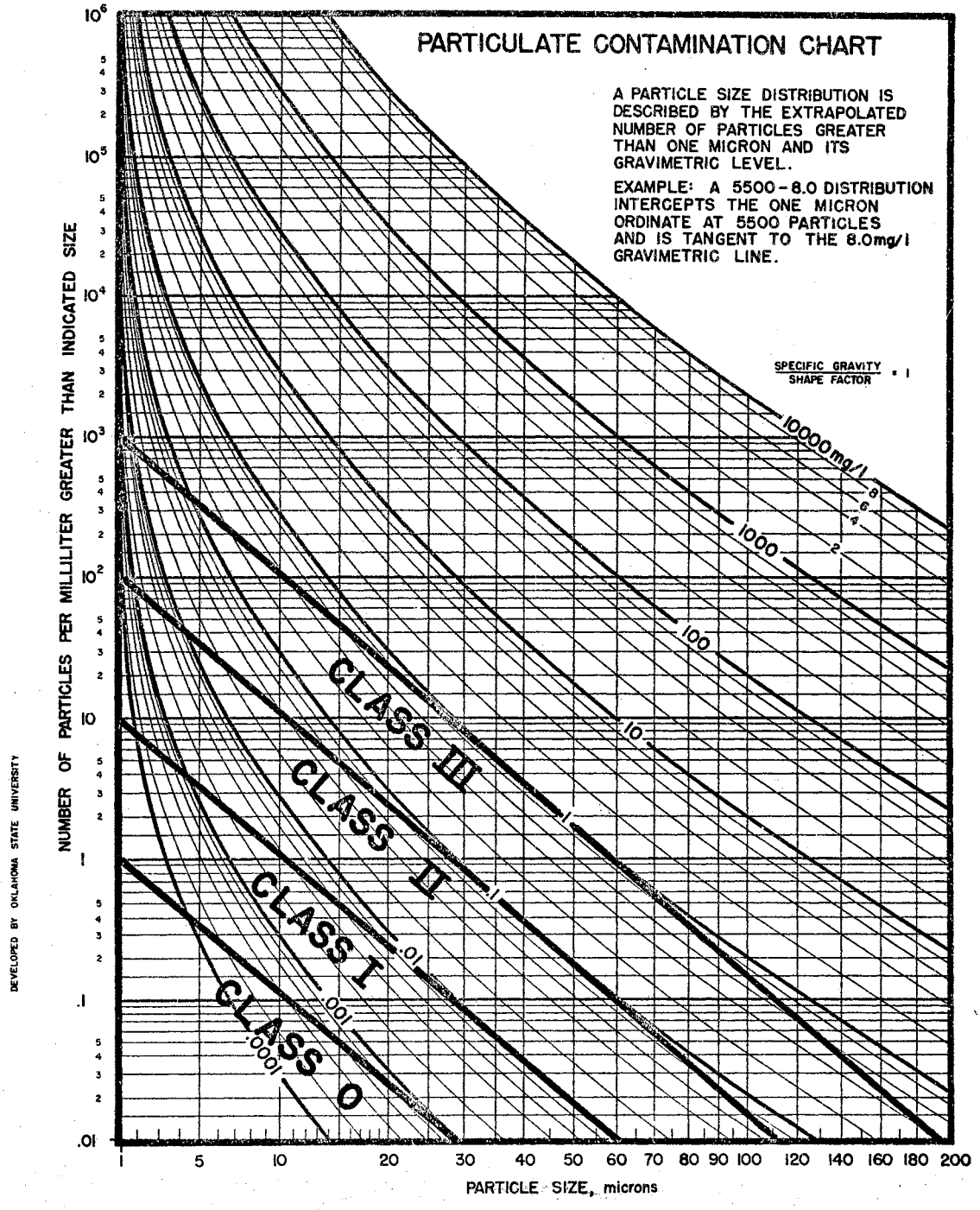


Figure 7. Sample Bottle Cleanliness Classes

level of the sample bottle must be two decades below the contamination level of the fluid sample if the resulting error is to be less than one per cent.

Requirements on Fluid Flow

Flow rate and fluid temperature are both critical to filtration performance testing. To prevent erratic efficiency results, the flow rate through the filter element being tested must remain constant. Also, the differential pressure is directly related to flow rate and viscosity by the laminar flow equation. By utilizing this equation, it can be shown that a one per cent variation in flow rate and a one per cent variation in viscosity can result in approximately four per cent variation in the differential pressure across the filter element. Since the differential pressure is used to determine the pressure characteristics of an element at the given flow rate and to establish the contaminant capacity, four per cent deviation is acceptable.

The fluid temperature is directly related to the fluid viscosity. In order to maintain viscosity within one per cent for a fluid such as Mil-H-5606, the fluid temperature must be maintained with a $\pm 2^{\circ}F$. Therefore, the control requirement for fluid temperature is that it must be maintained within $\pm 2^{\circ}F$ while the requirement placed on flow rate must be that it is controlled within ± 1 per cent of the rated flow.

Requirements of Pressure Differential Measurement

One of the objectives of the single-pass performance test is to produce a contaminant capacity curve. As a filter element traps and holds contaminant, there is a resultant rise in the differential pressure across the element. Because there are structural limits on the pressure drop that a filter element is capable of withstanding, it is very important to establish the relationship between the contaminant added to the filter element and the differential pressure. In light of this, the measurement of differential pressure becomes quite important.

The pressure differential across a filter element must be determined by measuring the pressure upstream and downstream of the element. The measurement of pressure in a flowing line is difficult due to the velocity of the fluid. SAE has published a recommended practice which covers pressure taps for this purpose. This publication is SAE ARP 24B and must be followed if accurate pressure measurements are desired.

Furthermore, requirements must be placed on the instrument to measure this differential pressure. Since high accuracy test gages are available which are capable of one-fourth of one per cent accuracy, they should be used for the single-pass performance test. Also, to further insure an accurate pressure differential measurement, both the upstream and downstream pressures must be read from the same

test gage unless a single, precise, differential pressure cell is used.

Requirements of Sample Analysis

The samples taken during a single-pass filtration performance test must be analyzed to determine the particle size distribution of the contaminant in these samples. There are two recognized techniques available to determine the particle size distribution of contaminant in a fluid sample. One technique involves optically counting the particles based on a procedure outlined in SAE ARP 598. This is a very time consuming and tedious procedure requiring skilled personnel. If a filtration performance test is to have general applicability, this procedure cannot be seriously considered.

The second technique involves the use of an automatic particle counter. This technique does not require highly skilled personnel and is a relatively fast method of determining the particle size distribution of contaminant in a fluid sample. The advantages of the automatic particle counting technique require that serious consideration be given to it for analyzing samples from the single-pass performance test. The one basic requirement, however, which must be placed upon the automatic counting technique is that it must correlate with the optical method.

The contamination analysis on the samples taken during performance testing must result in cumulative counts of

particles greater than 10, 20, 30, and 40 microns in diameter. By subtraction, the number of particles between 10 and 20, 20 and 30, 30 and 40 microns can be obtained from this data. The number of particles between 10 and 20 microns will be assumed to have an average size of 15 microns while the number between 20 and 30 microns and the number between 30 and 40 microns will be considered as 25 and 35 micron particles, respectively. The efficiency at each of these particle sizes must be calculated by subtracting the number of particles downstream from those upstream, dividing by the number upstream and multiplying by 100.

$$EFF = \frac{\text{upstream} - \text{downstream}}{\text{upstream}} \times 100.$$

Requirements of Test Sequence

In order to be certain that as much information as possible is obtained during the single-pass performance test, requirements must be established for the sequence of events. First of all, a background sample must be taken as a check on the background contamination level. It is important during this sampling period to have fluid flowing through the injection system as well as the main flow circuit. This provides a check on the complete system.

Following the background sample, a properly inspected element must be installed and a predetermined upstream contaminant environment established and upstream and downstream samples taken. This will enable an initial efficiency and

contaminant level capability of the element to be evaluated. The pressure drop measurement must be recorded after every contaminant injection to provide data for the contaminant capacity curve.

To provide a sufficient quantity of fluid in the sample bottles during the sampling period, a constant system pressure must be maintained. Since the pressure drop across the filter element will increase as contamiant is added, a variable orifice must be provided to maintain a predetermined constant upstream pressure on the filter.

After the initial efficiency sample is obtained, the filter must be loaded with contaminant until an increase in the pressure drop is experienced. This is a critical point in the life of a filter element. It is not uncommon for particular filter elements to display severe degradation in efficiency when the differential pressure starts to rise. Such a drop in efficiency means that the filter is unloading and will be reflected in the downstream contaminant level. In order to detect any change in the efficiency of the filter element, the predetermined contaminant environment must be again established and samples taken.

To complete the test, samples must be obtained when the differential pressures reaches 2-4 psid and again when the pressure drop reaches 13-15 psid. The 2-4 psid sample will be a further check on the possible degradation of performance as pressure drop increases. The 13-15 psid will determine the performance of the filter element as it

approaches the end of its useful life.

Before stopping the test, the filter element must be loaded to approximately 25 psid to complete the contaminant capacity curve. When the 25 psid pressure drop increase is reached, the test is concluded.

Implementation of Single-Pass Filtration Performance Test

Introduction

The requirements set forth in the preceding section established the criteria for implementation of each of the eleven critical aspects of the single-pass filtration performance test. In this section, the actual equipment utilized to implement each of the critical aspects will be discussed and the conformance with the necessary requirements will be evaluated.

Contaminant

AC Fine Test Dust is utilized as the test contaminant for the single-pass performance test. The distribution of this contaminant has been optically established both at Oklahoma State University and other laboratories. The fact that this distribution was determined by independent sources using different batches of AC Fine Test Dust verifies the consistency of the distribution. Furthermore, classification of this contaminant into different size ranges also indicates that the distribution is very consistent.

The fact that AC Fine Test Dust possesses properties similar to those of a contaminant encountered in field service has been attested to by both mobile equipment and component manufacturers. Because of this similarity, AC Fine Dust is utilized for a large portion of the contamination control work being done presently and is generally accepted by industry as an artificial contaminant.

AC Fine Test Dust is available from the AC Spark Plug Division of the General Motors Corporation and has been available for many years. This test dust is not expensive when obtained from AC Spark Plug Division in its full distribution form.

Contaminant Preparation

Because of the metering requirement placed on the contaminant, it is prepared in a slurry form. To insure that the contaminant within the slurry is thoroughly dispersed and completely oil wetted, a preparation procedure has been established. The slurry preparation procedures are as follows:

(1) Contaminant is accurately weighed and placed in a clean bottle. The cleanliness level of this bottle is not critical because of the high contaminant concentration being placed into it. Therefore, a Class II or III bottle is acceptable.

(2) Fluid extracted from the test system is

placed in the bottles containing the contaminant. Care is taken to leave sufficient air space in the slurry bottle for agitation.

(3) The bottle containing the contaminant and oil is agitated with a paint shaker for 10 minutes and then placed in an ultrasonic bath for 30 seconds to form a homogeneous slurry. Experience has shown that with an ultrasonic bath having a power level of 10 watts per square inch, the 30 second period is a maximum. Periods longer than 30 seconds will result in contaminant breakdown with a resulting distribution change.

Contaminant Injection

The contaminant injection system consists of a remotely operated solenoid valve to start and stop the injection, a timer to automatically stop the injection after a predetermined length of time, and a needle valve to regulate the injection flow rate. Also included in the contaminant injection system is a contaminant chamber where the contaminant slurry is entrained by the injection flow, an area-type flowmeter to measure injection flow rate, and an air-operated ball valve downstream from the contaminant chamber to isolate this chamber from the main flow when injection is not in operation.

In operation, a contaminant slurry is placed in the contaminant chamber, and the solenoid valve is activated. A valve is provided in the main flow stream which produces a pressure differential sufficient to force a small part of the main flow stream through the injection system. The timer is started simultaneously with the solenoid valve opening. The timer will automatically close the solenoid valve after a predetermined length of time has elapsed. The injection flow rate is preset prior to activation of the injection system; however, this flow rate can be manually regulated during injection. The fluid flowing into the contaminant chamber displaces the contaminant slurry and forces this slurry to enter the main flow stream at a turbulent point upstream of the test filter.

This injection system fulfills all the requirements established for an injection system to provide sufficient control of the upstream contaminant environment. It provides a means to regulate and measure the injection flow rate as well as a contaminant chamber in which the contaminant slurry can be placed. The material balance relationship holds for this injection system and the upstream contamination level can be predicted prior to injection.

Sampling

It has previously been required that samples taken during the single-pass performance test must follow dynamic sampling procedures. There are essentially two types of

dynamic sampling methods - isokinetic and turbulent. Isokinetic sampling requires the existence of laminar flow in the extraction section. Since it was found impossible to insure a true laminar flow condition, the turbulent sampling method is utilized for this filter performance test. Turbulent flow, by definition, produces a violent mixing action and provides a uniform particulate distribution in the flow stream. According to (14), several independent studies have shown that the quality of the sample is not dependent on the sampling flow rate or the probe configuration, if the sample is extracted from the main stream in a turbulent area.

Two samples are drawn from the main fluid stream at each required sample point of the performance test. One sample is extracted from a turbulent region between the contaminant injection point and the test filter. The other sample is taken from a turbulent region downstream of the test filter. Two methods have been found satisfactory to establish the turbulent region from which these samples are extracted. One method utilizes a turbulent sampling valve designed for this purpose. The other method makes use of the turbulent action resulting from a change of direction of the flow stream. An elbow is utilized for changing the direction of the flow stream; however, careful attention must be given to the flow rate and the size of the elbow to be certain turbulence does indeed exist. The sampling procedure used during this performance test follows the recommended practice for dynamic sampling proposed by Oklahoma

State University to the National Fluid Power Association in November, 1969.

The length of the sampling period will determine how much the samples which are extracted will be diluted. That is to say, if the material balance calculations applied to the injection system indicate that the contaminant chamber volume will be displaced in 10 seconds and the sampling period is 50 seconds, the samples will be diluted by a factor of five. This dilution has a very beneficial effect on the later analysis of these samples. The automatic particle counter which is used in the analysis of filtration performance samples has a definite limitation on the concentration of contaminant in the samples it evaluates. Properly diluted samples eliminate the necessity of further dilution during analysis and the potential error resulting from such dilution.

Background Contamination Level

The use of system fluid as dilution fluid in the sampling procedures places severe restrictions on the background contamination level. In order to fulfill the necessary requirements of the background contamination level, two high performance filter elements are placed in series in the main flow stream. These background control filters remove contaminant which is not removed by the test filter and prevent its recirculation. The single-pass designation for this test resulted from the prevention of contaminant

recirculation. It has been found that the inclusion of the background control filters meets the background contamination level requirements on all filters tested in this study. As the performance of filters improve, the background control filter requirement will have to be re-evaluated.

Test Filter Inspection

To evaluate the structural integrity of a filter element prior to testing its performance, the filter element is subjected to a bubble test. The bubble test consists of admitting filtered air into the center of the filter element submerged in a liquid such as alcohol and determining the air pressure at which the first bubble appears. Although experience has shown that the bubble test is not a reliable indication of filtration ability for depth media filters, the bubble test has application in determining the condition of end cap and seam seals. The complete bubble test procedure is as follows:

(1) The bubble test fluid (technical grade alcohol) is filtered through 0.45 micron Millipore paper and poured into a transparent tank.

(2) The filter element to be tested is placed horizontally in the transparent tank, so that it is covered by one-half inch of the bubble test fluid.

(3) Air is admitted within the filter element.

The air pressure is increased slowly using a regulating valve until the first bubble appears.

(4) The air pressure is reduced and the filter element is rotated. Step 3 is repeated.

(5) Step 4 is repeated until the element has been rotated 360°. If no bubbles are observed at the end cap or seams, the average pressure within the element when the first bubble appears is recorded in inches of water. Bubbles appearing at the end cap or seam seals of the element completely eliminates that particular element from further consideration.

Sample Bottle Preparation

Sample bottle cleanliness is a critical aspect in the determination of fluid contamination level. If the contamination level of the fluid in the bottle is very low, the cleanliness level of the bottle must be significantly lower. In fact, one of the requirements placed upon the sample bottles is that their contamination level be no more than one-hundredth that of the fluid being sampled. This means that for the high performance filter elements currently being manufactured, the sample bottles needed for their evaluation must exhibit a cleanliness level corresponding to a Class I bottle. To this end, a bottle cleaning

procedure has been established and is currently utilized to prepare sample bottles for the single-pass performance test. This bottle cleaning procedure was presented as a recommended practice by Oklahoma State University to the National Fluid Power Association in November, 1969.

Experience is a very important teacher in regard to sample bottle cleaning. Large errors can be incurred through extremely subtle mistakes in the cleaning technique used. Sample bottles utilized for filtration performance testing are distinguished from bottles used for other purposes. That is, they are not used for extracurricular activities such as slurry containers.

To insure that bottles used for precision sampling are not mixed up with other bottles, each sample bottle is permanently marked and coded. From these markings, the bottle history can be identified. Care is taken to see that a bottle marked as a sample bottle is never utilized for any other service.

Fluid Flow

Flow rate in the single-pass performance test system is controlled by the speed of a vari-drive and measured by a Fischer-Porter turbine type flowmeter. This flowmeter is accurate to within a .5 per cent which is less than the requirements established for flow measurement and control.

The system temperature is maintained at a predetermined constant value by a remote temperature controller.

A thermocouple is used to measure the temperature of the system fluid. The signal from the temperature thermocouple is compared to the desired temperature by the temperature control which regulates the flow of cooling water to a heat exchanger in accordance with the difference between the actual fluid temperature and the desired fluid temperature. Heat is supplied to the system on a continuous basis by a heater, thus insuring a continuous demand for cooling water. A small circulating pump is provided to circulate fluid from the system reservoir through the heat exchanger and heater back to the reservoir. The accuracy of the temperature control system is well within the $\pm 2^{\circ}$F. established as a requirement.

Pressure Differential Measurement

Pressure taps per SAE ARP 24B are included in the test circuit both upstream and downstream of the test filter. The pressure at each of these pressure taps is measured by a high accuracy test gage manufactured by the Heise Bourbon Tube Company, Inc. By manipulating two valves provided for this purpose, both the upstream and downstream pressure can be read from this gage, thereby eliminating some possible error. This gage is capable of measuring pressure to an accuracy of one-fourth of one per cent. The differential pressure is obtained by simple subtraction of the downstream pressure from the upstream.

Sample Analysis

As a result of the requirements placed upon the sample analysis method, an automatic particle counter is used to analyze samples taken during a filtration performance test. In addition, the requirement was placed upon the automatic particle counting technique that it must agree with particle counts made optically.

As a result of testing at Oklahoma State University utilizing an automatic particle counter manufactured by High Accuracy Products Corporation, it became apparent that the theoretical calibration factors suggested by the manufacturer would not produce particle counts from the automatic particle counter which would agree with counts made optically. Basically, the HIAC automatic particle counter can be accepted as an instrument which can be adjusted to exhibit a 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 theoretical calibration factors suggested by the manufacturer for use with this machine were determined by assigning a size value equal to the diameter of a sphere 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 lack of correlation between automatic particle counting techniques and optical particle counting prompted the establishment of a program to define a new calibration

criterion to be used with automatic particle counters. This criterion was based on an actual contaminant and due to the previously discussed advantages, AC Fine Test Dust was selected. The result of this program was a recommended standard calibration technique for liquid automatic particle counters. This standard calibration technique was presented by Oklahoma State University to the National Fluid Power Association in November, 1969.

The particle counter utilized in analyzing the samples of a single-pass filtration performance test is calibrated per this standard as well as several other machines throughout the country. Correlation between the two particle counting techniques has been acceptable when this calibration standard is utilized.

Test Sequence

The requirements on the test sequence prepared the way for the establishment of a complete single-pass filtration performance test procedure. This test procedure is outlined in the following steps:

(1) The filter element is placed in its appropriate filter housing and the rated flow suggested for the element is passed through it.

(2) A back pressure control valve is adjusted until 75 psi is established upstream of the test filter. The back pressure valve is

adjusted throughout the test to maintain 75 psi upstream pressure, thus insuring uniform sampling.

(3) A sample is taken upstream and downstream with the injection system activated prior to any contaminant injection as a check on background contaminant conditions. The initial pressure drop across the test filter is recorded.

(4) The calculated amount of contaminant is placed in the contaminant injection chamber and injected at the predetermined injection flow rate to establish a 75 milligrams per liter contamination level upstream of the test filter. An upstream and downstream sample is extracted during the injection and the pressure drop is recorded at the end of the injection period.

(5) Contaminant is injected in larger increments until a change in the pressure drop is observed. The pressure drop is recorded following each injection.

(6) At the first indication of a pressure differential rise, a 75 mg/l contaminant level is again established upstream of the test filter and samples are taken. Again, the

pressure differential is recorded at the conclusion of the injection.

(7) Contaminant is injected in smaller increments depending upon the rate of pressure drop increase until 2-4 psid increase in the pressure drop is obtained.

(8) The 75 milligrams per liter contaminant environment is again established and samples taken. The pressure drop is recorded.

(9) During the major loading period, contaminant is added in relatively large increments when compared to the contaminant required to establish the 75 mg/l level.

(10) The last sample point is when the pressure drop has increased to 13-15 psid.

(11) Injection of contaminant is continued until about a 25 psid increase in pressure drop is observed in order to complete the contaminant capacity curve.

Circuit Description

The circuit utilized in the single-pass filtration performance test was virtually designed by the implementation of the control requirements of each of the eleven critical control aspects. Figure 8 illustrates the circuit which is being utilized. In operation, fluid is drawn from the cone-shaped reservoir by a fixed displacement gear pump which is

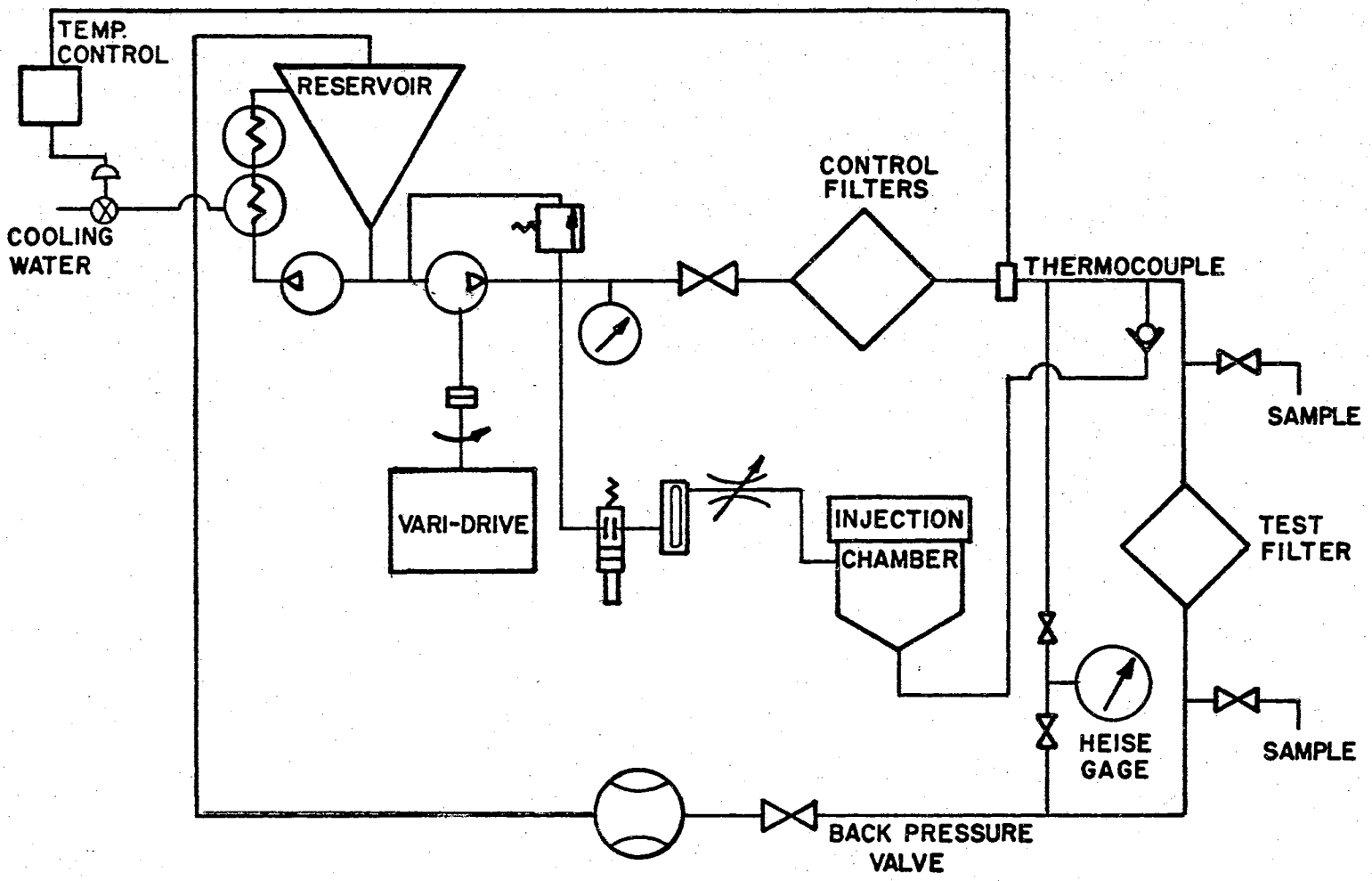


Figure 8. Circuit Schematic for Single-Pass Filtration Performance Test

driven by a remotely adjustable vari-drive. The reservoir is designed in such a manner as to provide maximum mixing without air entrainment and dead zones, thus insuring that the reservoir will not trap contaminant. The pump outlet is connected in series with a set of background control filters which insure rigid background contaminant control. A manually adjustable pressure relief valve is provided to protect the pump from accidental overpressurization. A manually operated flow control value is located at the entrance to the background filters to provide a source of medium high pressure for the contaminant injection system.

From the background filters, the fluid flow is directed through a turbulent section where a sample can be extracted to the test filter. After passing through the test filter, the fluid encounters another turbulent sampling section and proceeds on the back pressure control valve, which is utilized to maintain a constant pressure drop through the test loop. Downstream from the back pressure control valve, the oil passes through the turbine flowmeter and returns to the reservoir through a diffuser. The diffuser is provided in the reservoir to further insure thorough agitation of the fluid in the reservoir.

The contaminant injection system also shown in Figure 8 is fully described in the implementation section as is the temperature control sub-loop.

Presentation of Data

The efficiency and contaminant capacity results of the single-pass performance test are presented in the form of a filtration performance chart shown in Figure 9. In order to place the contaminant added on a specific contaminant added basis, it is divided by the area of the test filter.

The element distribution rating is established by recording the number of particles per milliliter greater than 10 and 20 microns contained in the downstream efficiency samples on the Particulate Contamination Chart. The filter element distribution rating is determined by the straight distribution line passing through the largest number of 10 and 20 micron particles recorded on the Particulate Contamination Chart. The rating line is designated by the intercept on the ordinate or the number of particles greater than one micron and the gravimetric line to which it is tangent. Figure 10 illustrates an element rating line. The filter element rating shown in Figure 10 is designated as a 150000-32 because it intercepts the ordinate axis at 150000 and is tangent to the 32 milligrams per liter gravimetric line.

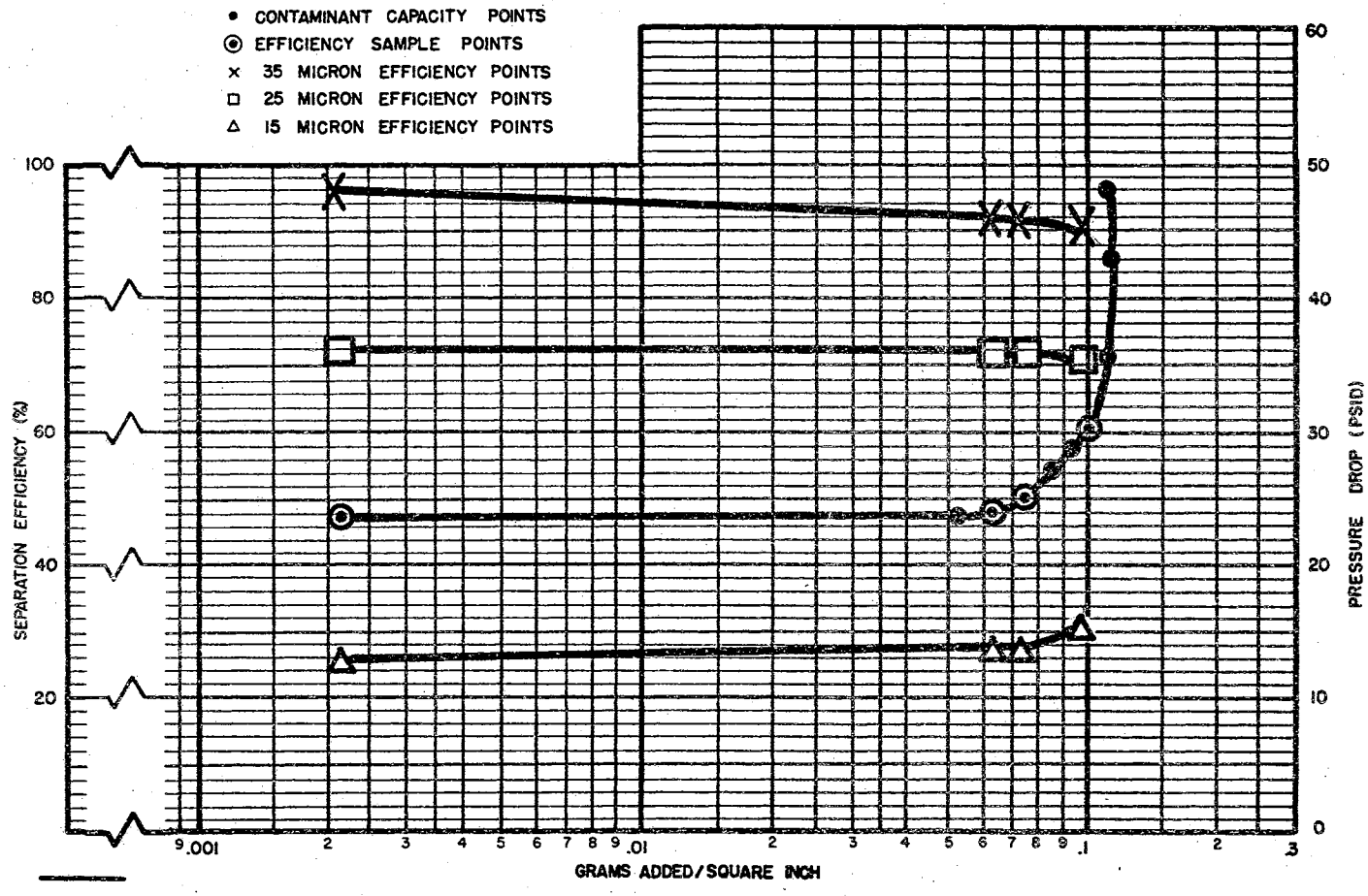


Figure 9. Typical Filtration Performance Chart

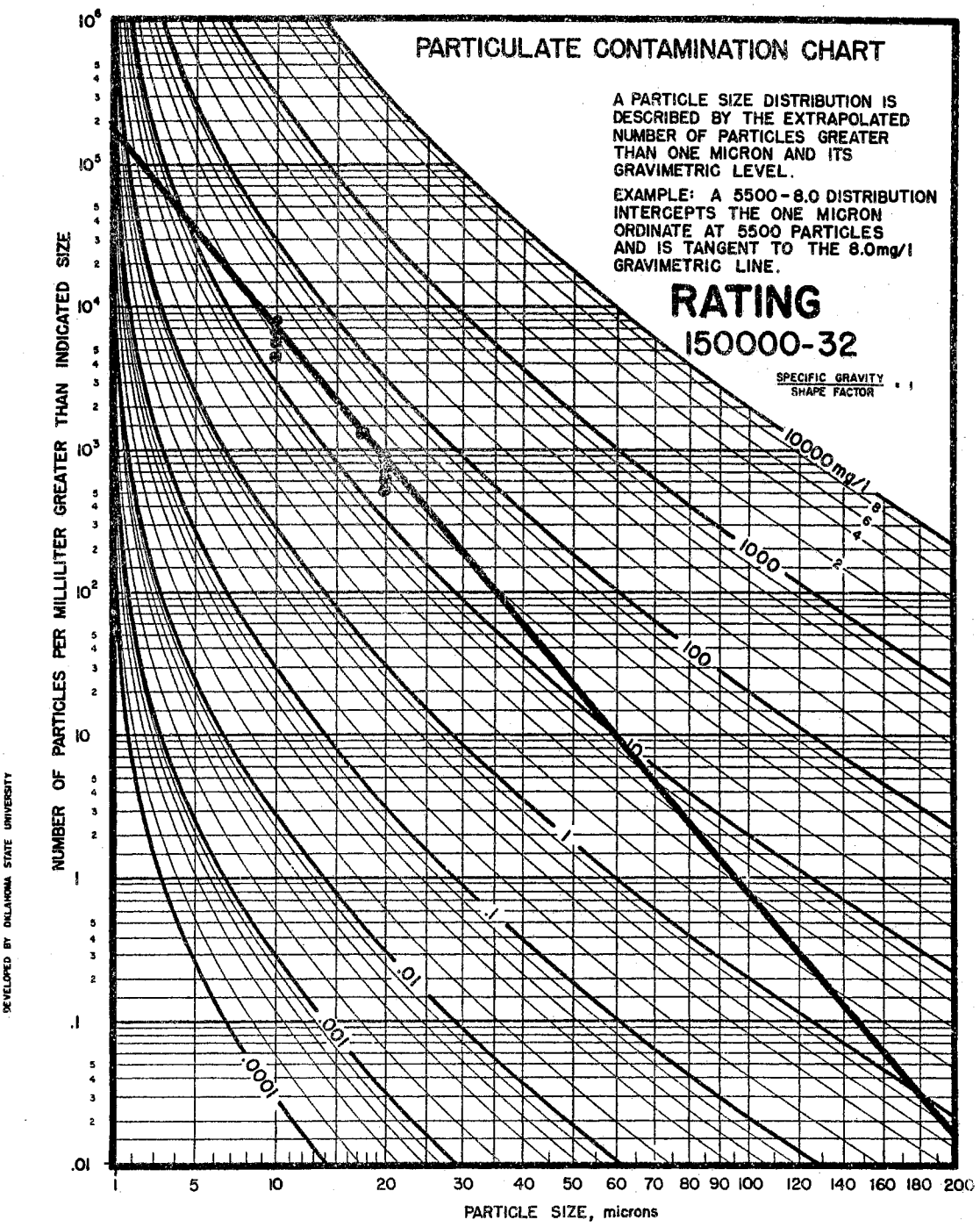


Figure 10. Typical Downstream Distribution Rating

CHAPTER IV

PRESENTATION OF RESULTS

Introduction

Many filtration performance tests have been conducted using the single-pass concept. The results of some of these tests will be presented in this chapter for the purpose of illustrating the repeatability of the single-pass filtration performance test and also to demonstrate its ability to generate information that is unique to a specific filter.

Repeatability

In order to illustrate the repeatability of this performance test, the results of two different tests conducted on two different elements is presented. Table I illustrates the results of two tests on a filter element which will be designated as Filter 1.

Table II shows the efficiency data of the two tests on Filter 1.

The data presented in Table I indicates that the test repeated the contaminant capacity of filter element 1 within approximately eight per cent. It is very difficult to calculate a per cent deviation on the distribution ratings;

TABLE I

SINGLE PASS FILTRATION PERFORMANCE TEST RESULTS
(FILTER 1)

	Bubble Point H_2O	Contaminant Capacity gm/sq in	Distribution Rating
Test 1	15	.023	100000-6.3
Test 2	17.5	.025	110000-7.0

TABLE II

EFFICIENCY DATA
(FILTER 1)

	15 Micron		25 Micron		35 Micron	
	Test 1	Test 2	Test 1	Test 2	Test 1	Test 2
Sample Point 1	99.6	98.5	99.4	98.6	99.5	98.6
Sample Point 2	99.6	98.3	99.4	98.6	99.6	98.6
Sample Point 3	99.8	99.0	99.7	98.7	99.4	98.9
Sample Point 4	95.8	94.3	98.6	97.5	99.4	98.4

however, it is obvious that the two test produced very close results.

Table II shows that the efficiency data did not deviate more than two per cent on any of the sample points.

Table III illustrates the results of two tests on a filter element which will be designated Filter 2.

TABLE III

SINGLE PASS FILTRATION PERFORMANCE TEST RESULTS
(FILTER 2)

	Bubble Point H_2O	Contaminant Capacity gm/sq in	Distribution Rating
Test 1	7.5	.041	85000-25
Test 2	7.4	.038	90000-25

The data shown in Table III indicates a deviation of contaminant capacity of 7.3 per cent and very close agreement on the distribution ratings.

The efficiency data resulting from these two tests on Filter 2 is shown in Table IV.

TABLE IV

EFFICIENCY DATA
(FILTER 2)

	15 Micron		25 Micron		35 Micron	
	Test 1	Test 2	Test 1	Test 2	Test 1	Test 2
Sample Point 1	80.9	80.6	98.9	98.4	99.6	99.4
Sample Point 2	81.9	80.3	98.9	98.6	99.4	98.6
Sample Point 3	82.4	83.3	98.4	98.8	99.3	99.7
Sample Point 4	82.6	89.0	98.7	99.3	99.5	99.9

In examining the data of Table IV, it can be seen that the maximum deviation occurred between sample point 4 in the 15 micron efficiency value. This deviation is approximately 7.5%.

Table V summarizes the results of these four performance tests. These results certainly indicate that the single pass filtration test is repeatable since much of the deviation between these two filter performance tests probably stems from element manufacturing variation.

TABLE V

SUMMARY OF FILTRATION PERFORMANCE RESULTS

	Maximum Deviation Filter 1 (%)	Maximum Deviation Filter 2 (%)
Contaminant capacity	8	7.3
Efficiency	2	7.5
Distribution rating	Very close	Very close

Contaminant Unloading

The pore structure of a filter medium establishes its capability to achieve and maintain a given contamination level for a specific length of time at a given pressure loss. The structural integrity of both the element and the medium determines whether an element will exhibit significant changes in separation efficiency as it traps contaminant and experiences an increase in differential pressure. It is not uncommon for particular filter elements to display severe degradation in efficiency and distribution rating when the differential pressure begins to rise. The results of a single-pass filtration performance test conducted on such an element vividly illustrates this change in performance. Figure 11 is a filtration performance chart and Figure 12 is a particulate contamination chart summarizing the results of a single-pass test run on Filter 3.

Figure 11 shows that the efficiency of the element

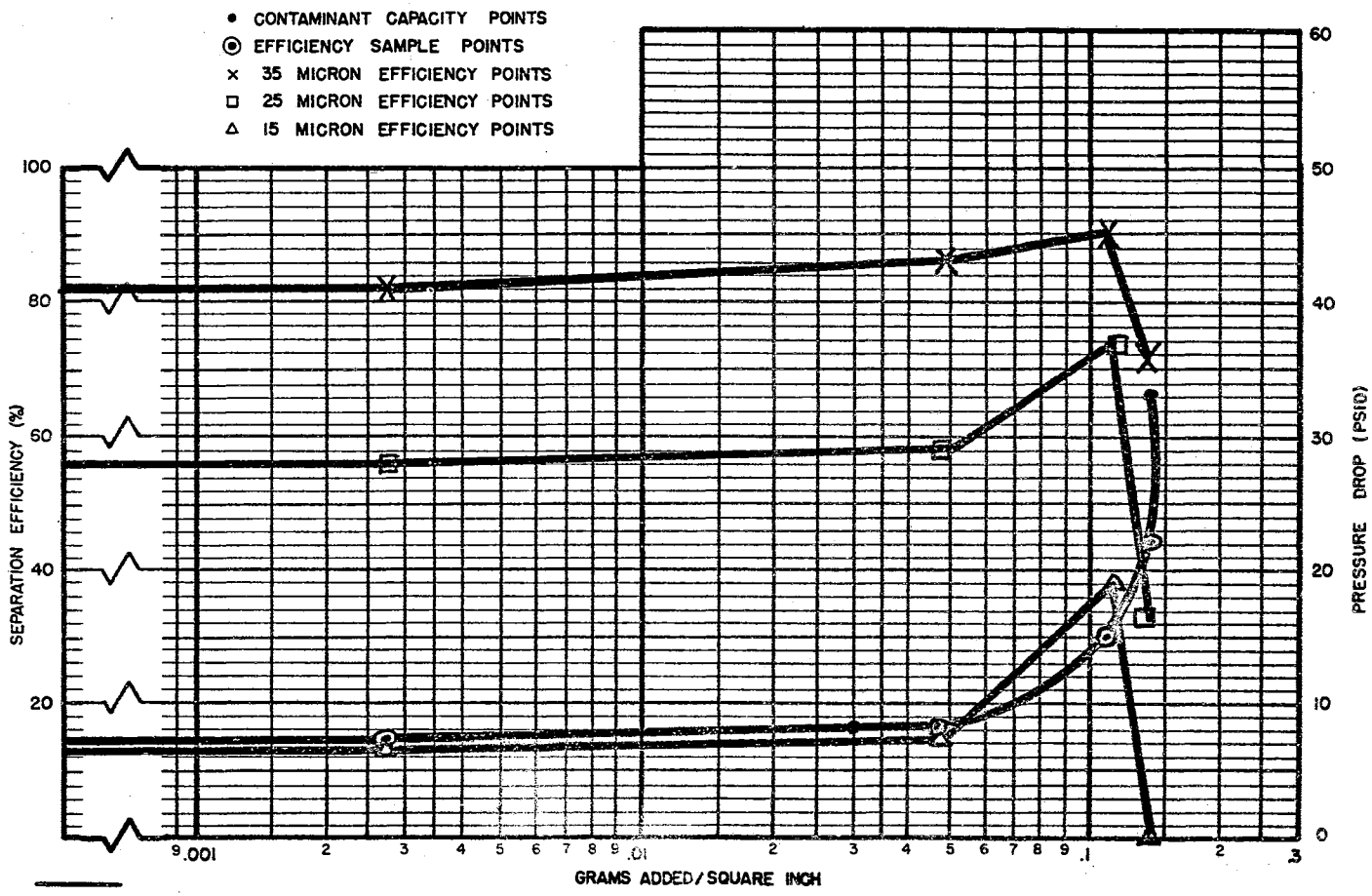


Figure 11. Filtration Performance Chart for Filter 3

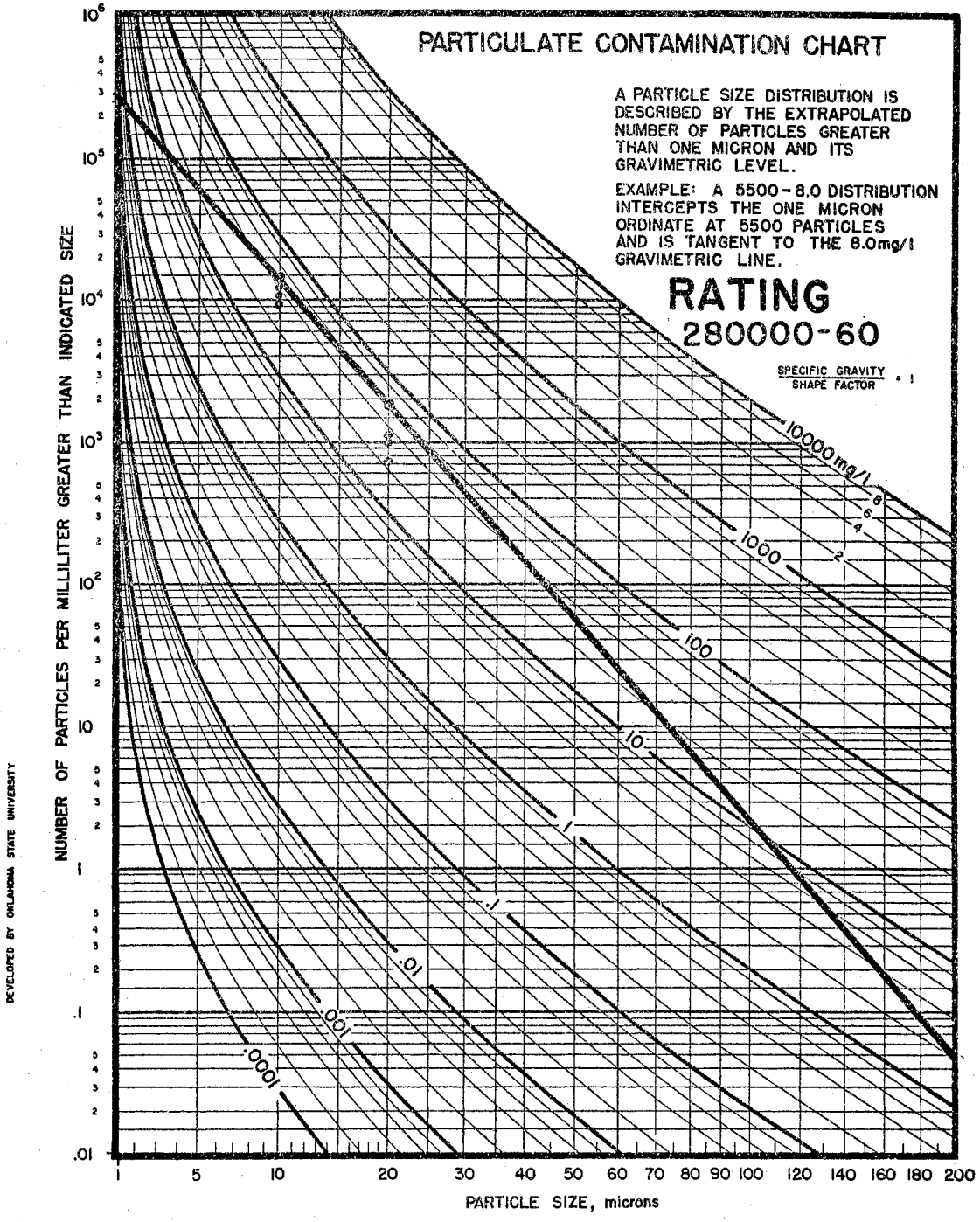
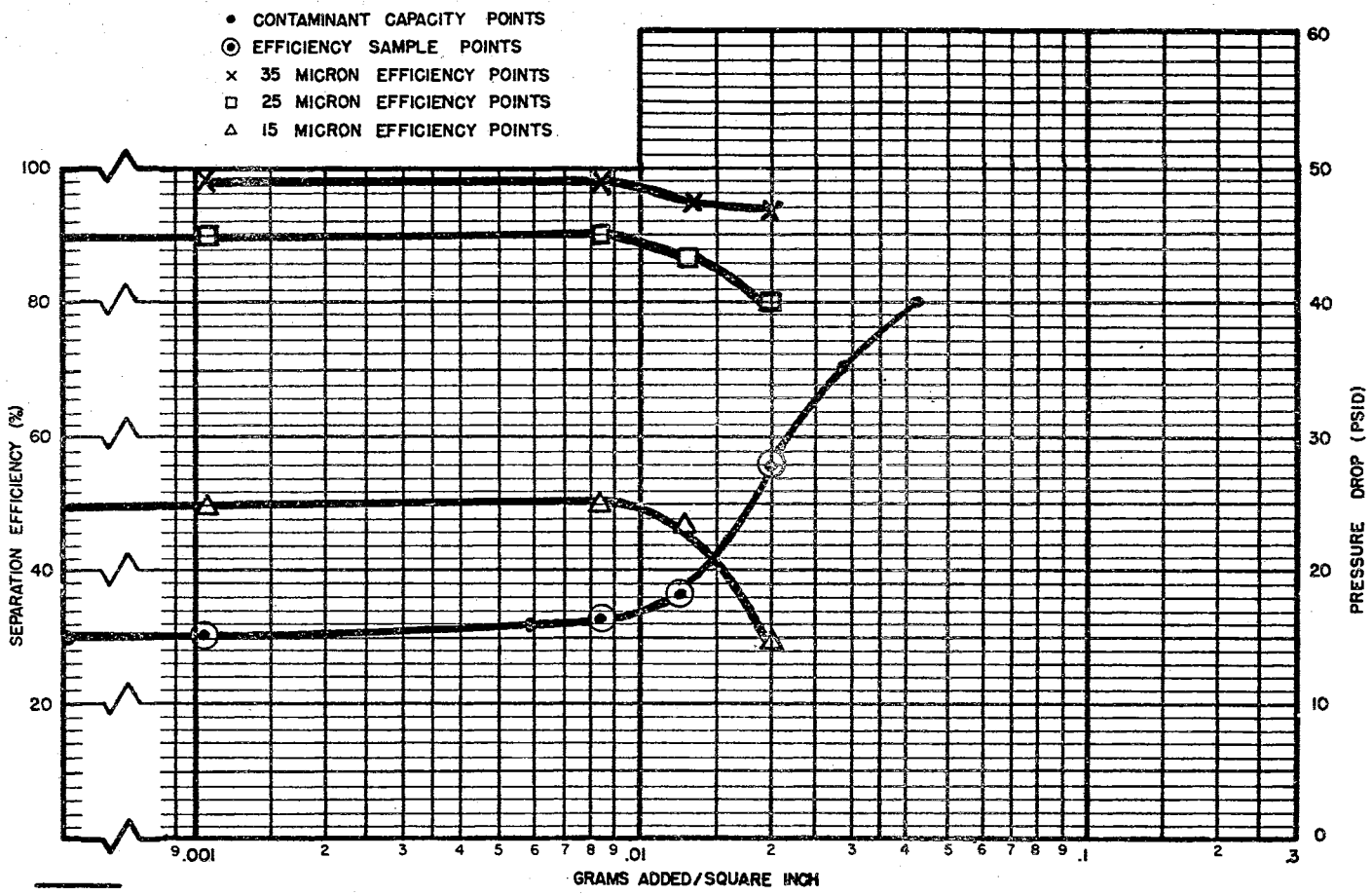


Figure 12. Downstream Distribution Rating for Filter 3

began to increase slightly as it was loaded with contaminant. However, as the differential pressure increased, the element suffered a severe structural failure resulting in an efficiency decrease at all three particle sizes evaluated. Figure 12 shows the resulting change in the element distribution rating as this failure occurred.

The filter performance illustrated in Figures 11 and 12 is known as "dumping" and a filter element exhibiting this type of performance is called a "dumper". Dumping can be exhibited in at least two different ways. The dumping characteristic of Filter 3 is known as "classical dumping" since there is no indication that this condition exists until the samples are analyzed. Manufacturers sometimes produce a "dumping type element" and never realize that it exhibits this type of performance. The second type of dumping is illustrated by Filter 4 shown in Figure 13. This type of contaminant unloading or dumping will be evident while the single-pass filtration performance test is being conducted. The filter begins to exhibit the classical dumping characteristic as the differential pressure rises. However, as the differential pressure continues to rise, the contaminant capacity curve "drooped", resulting in the shape of the curve shown in Figure 13. Since a filter element exhibiting this type of performance can be distinguished by a simple contaminant capacity test it is not common to find an element which displays this characteristic.



FILTRATION PERFORMANCE CHART FOR ELEMENT FILTER 4

Figure 13. Filtration Performance Chart for Filter 4

Effects of Flow Rate

The effect of flow rate upon the performance of a filter element can best be illustrated by showing the results of single-pass performance tests conducted on three similar elements at three different flow rates. Obviously, there is some flow rate high enough to impair the performance of an element; however, the results of the performance tests conducted on three similar elements would indicate that the performance of a filter element is improved as flow rate increases. It is apparent that these performance tests were conducted at flow rates below the maximum flow rate that the filter was capable of handling. Table VI shows a summary of the results of the performance tests performed on Filters 5, 6, and 7, which were similar elements.

TABLE VI

EFFECT OF FLOW RATE

Element Number	Flow Rate GPM	Specific Contaminant Capacity	Distribution Rating
5	9	.046	1500000-37
6	30	.040	900000-25
7	45	.036	570000-15

The results shown in Table VI demonstrate that the single-pass test is capable of distinguishing the difference in the performance of a filter element as operational parameters are changed.

Typical Filter Distribution Ratings

As a result of the filtration performance testing conducted at Oklahoma State University, it was recognized that each filter exhibits the capability to produce a unique downstream contaminant distribution. The fact that this unique distribution does in fact exist was demonstrated by the results of many single-pass filtration performance tests.

A wide variety of filter elements have been tested. The downstream contaminant distribution ratings of nine of these filters are shown in Figure 14. The filter elements represented in Figure 14 were selected to demonstrate the uniqueness of the downstream distributions and the wide range of filters that have been tested (see Table VII).

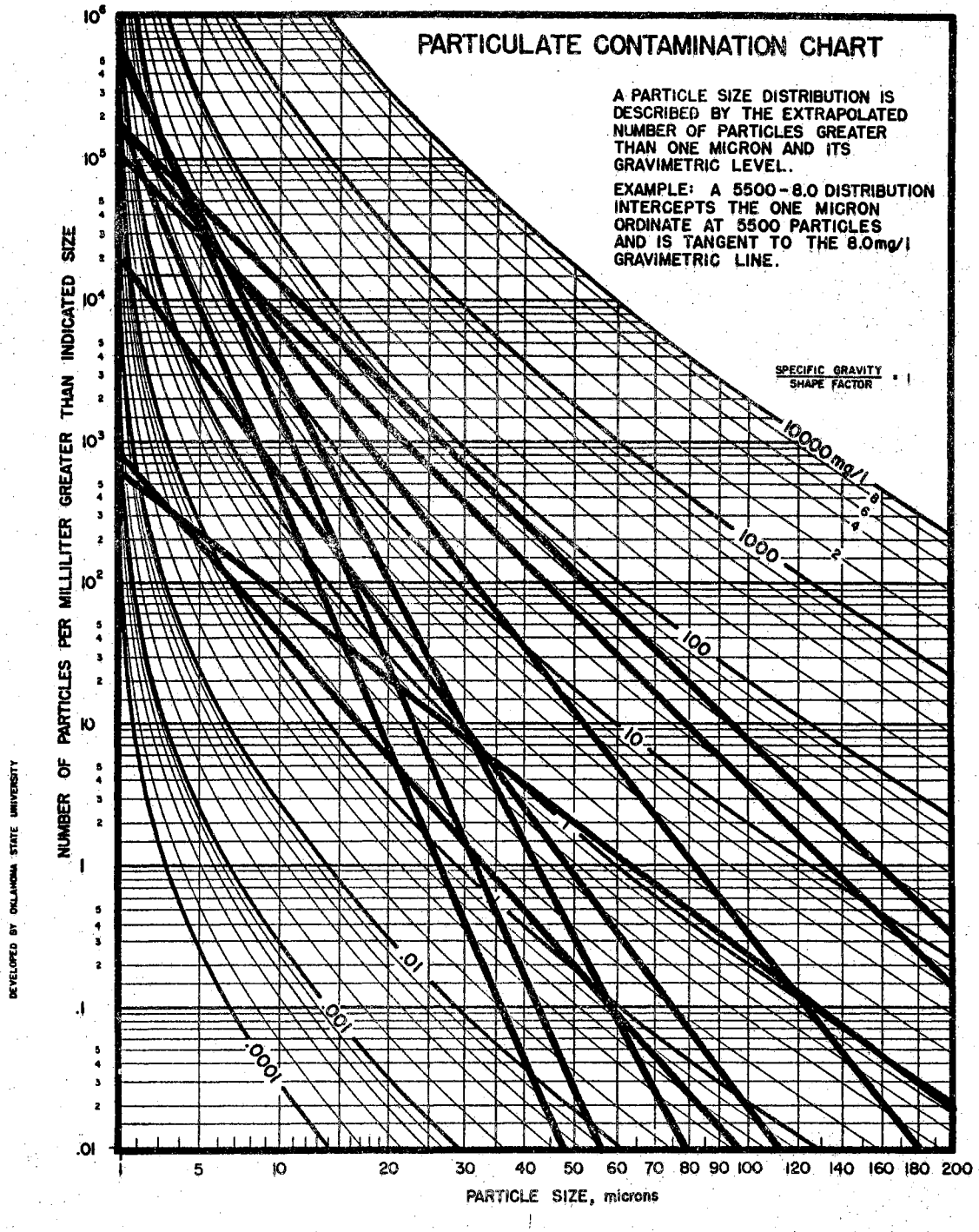


Figure 14. Range of Downstream Distribution Ratings

TABLE VII

TYPICAL RESULTS OF FILTER PERFORMANCE TESTS

Element Number	Bubble Point (in. of water)	Contaminant Capacity gms/sq in	Distribution Rating
8	5.0	.074	160000-20
9	7.0	.136	100000-40
10	7.4	.037	500000-15
11	4.5	.190	160000-75
12	8.0	.089	440000-15
13	11.0	.030	580-1.2
14	17.5	.026	18000-2.0
15	19.0	.034	720-0.2
16	7.5	.064	160000-3.2

Summary of Results Presentation

The results presented in this chapter serve to illustrate among other things that the single-pass filtration performance is repeatable. The results of performance tests on Filters 1 and 2 show a maximum of eight per cent deviation in contaminant capacity, a maximum of seven and one-half per cent deviation in efficiency, and the qualitative evaluation of the distribution ratings indicated a very close correlation. The single-pass performance test is also capable of providing information peculiar to a specific filter, such as unloading characteristics and performance variation due to operational parameter changes.

CHAPTER V

SUMMARY AND CONCLUSIONS

Summary

This thesis considers the problems of evaluating filter performance factors. It is proposed that these performance factors can best be evaluated by a single-pass filtration performance test. The basic concept of this test is not new; however, until this development program was established at Oklahoma State University, the control concepts which are so necessary to this test had not been established. The development of these basic control concepts required a detailed study of each critical aspect of a filtration performance test and its relationship to other critical parts of the test. The implementation of the control concepts developed for each critical aspect lead to a complete test apparatus, which can be utilized to successfully conduct a fully controlled single-pass filtration performance test.

All three of the filter performance factors used to appraise the performance of a filter are revealed by the single-pass performance test. The pressure-flow characteristics and contaminant capacity are both revealed by the contaminant capacity curve derived as a result of this test.

Using the 75 mg/liter upstream environment as a reasonable yet severe base, the contaminant distribution rating can be determined from the contaminant analysis of the downstream sample. In addition, multiple filter efficiencies obtained as a result of this performance test can be utilized to further evaluate the contaminant trapping ability of a filter element.

Conclusions

The results of the single-pass filtration performance test verified that it is indeed repeatable. Contaminant capacity data agreed within eight per cent while efficiency data agreed within seven and one-half per cent. Although the distribution ratings cannot be compared on a per cent deviation basis, it is obvious that there was excellent agreement between the distribution ratings of similar elements.

Since the single-pass performance test was developed from the point of view of the fluid power user, it can best be utilized to rigorously define his needs. When the fluid power designer is able to define his requirements in a realistic manner, a progressive filter designer should be able to provide a filter element to satisfy the system.

Recommendations for Further Studies

Many new aspects concerning the operation of a filter in a flowing system were revealed by the filtration

performance work at Oklahoma State University. The results of single-pass performance tests on a wide variety of filters illustrate the fact that a filter element is not capable of removing all of the contaminant present in the fluid passing through it. Therefore, the contaminant level upstream of a filter in a field system is not constant, but instead varies as a function of the generation rate, the ingression rate, and the performance of the filter. In other words, the contaminant which escapes the filter is recirculated through the system back to the filter. The single-pass performance test is capable of distinguishing the unique contaminant removal capability of a filter and is sensitive to small changes in performance. However, it is recommended that a filter performance test should be investigated which would simulate the contaminant recirculation or multi-pass characteristics of a field system. Also, the generation and ingression rate should be reflected by continuous contaminant injection techniques.

SELECTED BIBLIOGRAPHY

(1) Kozeny, J. S.-Ber. Wiener Akad, Vol. 136 (1927), 271.

(2) Carman, P. C. Trans. Inst. Chem. Eng. Lond., Vol. 15 (1938), 150.

(3) Green, L., and P. Duwez. "Fluid Flow Through Porous Metals." Journal of Applied Mechanics, Vol. 73 (March, 1951), 39-45.

(4) Grace, H. P. "Structure and Performance of Filter Media." A.I.Ch.E. Journal, Vol. 2 (September, 1956), 307-336.

(5) Seed, R. G., and A. A. Foule. A General Study of Diverse Filtration Phenomena With Possible Applications to Aircraft Fuel Filtration. Wright Air Development Center Report No. 54-181 (November, 1952).

(6) Cranston, R. W. "Filtration of Fine Particles." Aircraft Engineering, Vol. 24 (June, 1952), 154-159.

(7) Fitch, E. C. A Basic Science Program in Filtration Mechanics. Oklahoma State University Engineering Bulletin No. 126 (1963).

(8) Tucker, R. H. "The Development and Verification of Theoretical Models for the Performance of Wire Cloth Filter Media." (Unpub. Ph.D. dissertation, Oklahoma State University, 1966.)

(9) Hermans, P. H., and H. L. Bredee. Rec. Trav. Chim., Vol. 54 (1935), 680.

(10) Gonsalves, V. E. Rec. Trav. Chim., Vol. 69 (1950), 873.

(11) Stone, K. L. "A Study of the Effects of Filter Housing Design and Contaminant Size on the Contaminant Capacity of a Wire Cloth Filter Element." M.S. Report, Oklahoma State University, 1965.

(12) Ludvig, E. Evaluation of Filter Media. Purolator Products Report No. 2633 (March 23, 1960).

(13) Casaleggi, C., E. Ludvig, and H. L. Forman. Evaluation of Low Pressure Aircraft Fuel Filters. Wright Air Development Center Report No. 55-317 (September, 1953).

(14) Filtration Mechanics Project Annual Report - 1967-68. Prepared for George C. Marshall Space Flight Center, Huntsville, Ala., by School of Mechanical and Aerospace Engineering, Oklahoma State University, Stillwater, Okla. (July, 1968).

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