INITIAL DEVELOPMENT OF A BOILING-PRESSURE TEST FOR WIRE CLOTH FILTER ELEMENTS

By

ROBERT ERNEST REED

Bachelor of Science
Mississippi State University
State College, Mississippi
1960

Submitted to the Faculty of the Graduate School
of the Oklahoma State University of
Agriculture and Applied Science
in partial fulfillment of
the requirements for
the degree of
MASTER OF SCIENCE
May, 1963

INITIAL DEVELOPMENT OF A BOILING-PRESSURE TEST FOR WIRE CLOTH FILTER ELEMENTS

Thesis Approved:

E C Fitch Jr.

Thesis Adviser

Dean of the Graduate School

ACKNOWLEDGMENTS

For helping to make the first year of graduate study at Oklahoma State University and this thesis possible, the writer wishes to express his appreciation and indebtedness to the following individuals:

To Dr. J. H. Boggs, Head of the School of Mechanical Engineering, for the research assistantship which the writer has held while attending Oklahoma State University for the past year.

To Dr. J. D. Parker who also was personally instrumental in extending the research assistantship to the writer.

To Professor E. C. Fitch who first extended membership on his research team to the writer and has directed the research for this thesis. His direction and encouragement have been all inspiring to the writer.

To fellow research assistants, R. E. Bose, J. E. Bose, C. R. Gerlach, M. W. Zaloudek, R. H. Tucker, and Dean DeMoss, for their able assistance to this endeavor.

To his wife, Lorena, for her direct efforts and encouragement during the past year.

To Messrs. John A. McCandless, George Cooper, and Ben Benjamin for their technical advice and assistance.

In addition, gratitude is expressed to Mr. Dale Neff, who made the drawings included in this thesis and Mrs. Dale Neff who typed the manuscript.

Robert Ernest Reed

TABLE OF CONTENTS

Chapter		Page
I.	INTRODUCTION	1
II.	PREVIOUS INVESTIGATIONS OF THE BUBBLE TEST AND ITS MODIFICATIONS	12
III.	STATEMENT OF PROBLEM	16
IV.	THEORETICAL ASPECTS	18
V.	REQUIREMENTS ON THE DESIGN OF APPARATUS.	22
VI.	SUPPORT EQUIPMENT	27
VII.	DATA AND RELATED ILLUSTRATIONS.	35
VIII.	DISCUSSION OF RESULTS, CONCLUSIONS, AND RECOMMENDATIONS	45
A SELECTED BIBLIOGRAPHY		49
APPENDIX		50

LIST OF TABLES

Table Page

7-1 Experimental Bubble-Pressure and Boiling-Pressure Data 36

7-2 Calculated Pore Diameters and "Average" Pore Diameter 37

7-3 Experimental Hydraulic Pressure-Drop and Air Pressure-Drop Data 38

7-4 Calculated Values of N_H and N_A 39

LIST OF ILLUSTRATIONS

Figure		Page
1-1	Typical Wire Cloth, "Rigimesh", Filter Element	3
1-2	Typical Weaves Used in Manufacturing Filter Elements .	4
1-3	Pore Size Distribution Curves	8
1-4	Hypothetical Pore Size Distribution Curve	10
2-1	Nominal Micron Rating vs Boil Point Micron Rating . .	14
5-1	Oklahoma State University Bubble Test Stand	23
5-2	Diagram of Oklahoma State University Bubble Test Circuit	25
5-3 (a)	Filter Element Mounting Spindle	26
5-3 (b)	Modification Incorporated for Boiling Test	26
6-1	Artificial Contaminant Loading Stand	28
6-2	Flow Diagram for Loading Stand	29
6-3	Typical Curves for Determining Dirt Holding Capacity .	32
7-1	"Hydraulic Pore Number", N_H, vs ADC (Actual Dirt Holding Capacity)	40
7-2	Inverse of Hydraulic Pressure Drop, 1/P, vs ADC . . .	41
7-3	Inverse of Air-Pressure Drop, $1/P_A$, vs ADC	42
7-4	"Air Pore Number", N_A, vs ADC	43

FOREWARD

This investigation represents a portion of the duties of the author while assigned to the Fluid Contamination Project as a graduate research assistant. The Fluid Contamination Project was conducted for the Directorate Material Maintenance of the Oklahoma City Air Material Command under contract number AF 34(601)-9879.

CHAPTER I

INTRODUCTION

Closed fluid power systems have reached a state of refinement where the contamination level of the fluid medium is more than ever a critical design and operational parameter. Moreover, the recognition by fluid power engineers of the malignity of contamination to the hydraulic system has initiated much thought pertaining to the origin and hence the control of fluid contamination below specified levels.

Relative motion of the various contacting parts, erosion of the mechanical components due to fluid flow, and cavitation are major contributors of noncompressible contaminant particles in a hydraulic system. The generation of particles within a system necessitates continuous filtration, at least, if the contamination level is to remain within limits.

Broadly, surface type and depth type are the two type-categories under which fluid filter media are classified. Each type, surface and depth, exhibits some characteristics of the other and simple categorizing is not always possible. Depth media depend on tortuous paths through the material to remove particles. On the other hand, surface media depend on the openings available for clogging at the outer periphery of the media.

Stainless steel wire cloth elements are categorized as being of the surface type. Because of certain properties, this type of filter element has become very popular. It is employed in many aircraft hydraulic installations. Two very definite advantages of the wire cloth filter element are its structural strength reliability under adverse conditions, and its cleanability. Fig. 1-1 shows a wire cloth, "Rigimesh", element which is manufactured by Aircraft Porous Media, Inc. The surface area of this filter is increased several times by convoluting the wire cloth during fabrication of the element. Changes of pore size, due to pressure variation across the wire cloth element, are eliminated by sintering the wires at the contact points in the weave. Fig. 1-2 illustrates some of the weaves incorporated in the manufacture of wire cloth elements. Aircraft Porous Media, Inc. uses the Dutch twill weave in some of their "Rigimesh" elements, and they claim that, "This weave prevents long, narrow fiber-type particles from passing through the filter." It is readily apparent that a pass through the twilled weave is much more tortuous than a pass through the less complex square weave.

Because of the availability to this thesis research, wire cloth filter elements with the Dutch twill weave, manufactured by Aircraft Porous Media, Inc., have been used exclusively in the experiments which are reported in this paper.

It is out of attempts to develop suitable cleaning methods for filter elements that a need for dependable nondestructive testing (tests that do not contaminate an element during the process) methods has grown.

Military specifications MIL-F-5504A, MIL-F-5504B, and

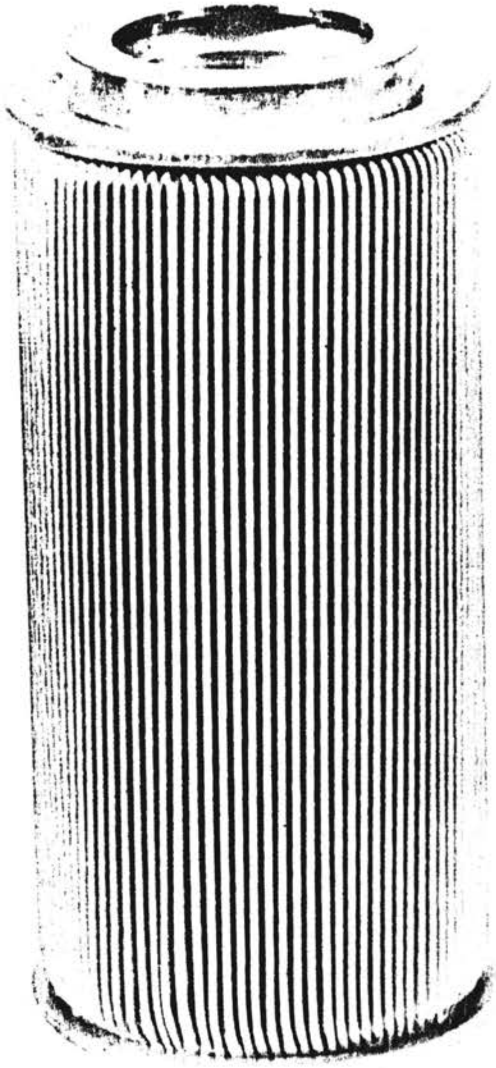
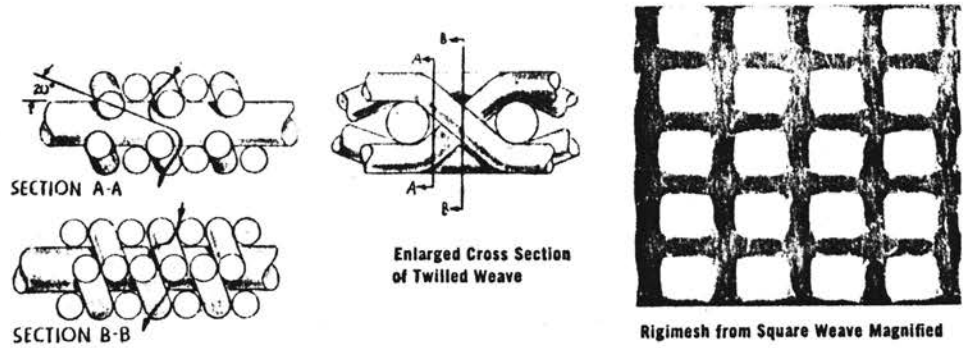


Fig. 1-1 Typical Wire Cloth, "Rigimesh", Filter Element



Enlarged Cross Section of Twilled Weave

Rigimesh from Square Weave Magnified

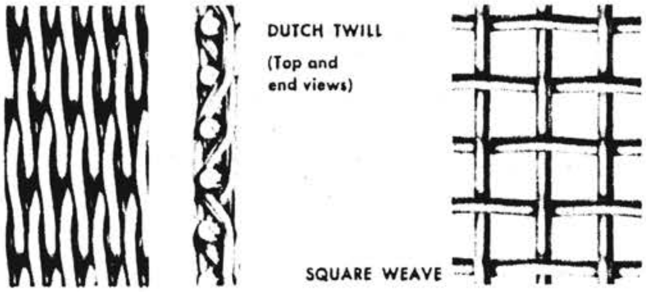


Fig. 1-2 Typical Weaves Used in Manufacturing Filter Elements

MIL-F-8815 are well established standards for aircraft filter media. Even these specifications are not to be thought of as industrial standards. The "A" version describes by definition that a 10-micron rated filter removes 97% by weight of all particles above 10 microns of a particular contaminant (AC fine test dust). The "B" version describes a 10 micron filter as being capable of removing 95% by weight of 10 to 20 micron glass beads. The 5504A and B specifications are referred to as nominal ratings. MIL-F-8815 defines an absolute rating for a filter media. This rating is determined by measuring the diameter of the largest glass bead to pass through a filter.

The bubble-pressure method has been generally accepted in the field as a means by which the size of the largest pore in a filter element can be determined. The filter cartridge is submerged to a horizontal mounting in a fluid (Solox 190 alcohol is commonly used) with known surface tension. Low pressure air is then allowed to enter the core space of the filter to displace the alcohol. Finally, only the surface tension of the fluid covering each pore prevents breakthrough of the air. By slowly increasing the air pressure in small increments of pressure change and carefully rotating the element, surface tension will be overcome first at the largest pore opening, and continuous bubbling is accomplished. The crux of this test is that pressure is inversly proportional to pore size (expressed as circular). This test is described in detail in Appendix A. Results of this test match the previously mentioned glass-bead test very closely.

Dirt holding capacity for a particular filter element is a design specification which defines the amount, by weight, of a certain artificial contaminant (AC fine test dust is commonly prescribed) that a filter element can be expected to hold. This specification is further qualified by stating the flow rate, fluid viscosity, filter installation in the test stand, range or limit of pressure drop across the filter, and the method of injecting the contaminant into the hydraulic fluid upstream of the element. All dirt holding capacities reported in this paper have been determined in the Oklahoma State University Fluid Contamination Laboratory using equipment that was designed and fabricated by Oklahoma State University personnel. Filter elements are installed in their companion housings, flow is held at the design rate, fluid temperature is maintained at 100° F, and contaminant is systematically injected into the main fluid stream in a slurried state. Excellent results are achieved in tests conducted with this equipment. The test procedure is described in detail in Chapter VI.

Note that the established testing methods discussed up to this point, with the exception of the bubble-pressure test, require that the element be installed in a hydraulic test system and actually perform as a filter to some standard contaminant. This fact eliminates the usefullness of these tests for evaluating the probable performance capacity of a clean filter element. If wire cloth filters are due to be cleaned and then declared fully recapacitated for service, the demands for precision qualitative and quantitative, but yet nondestructive, testing methods are justified.

Attempts have been made at Oklahoma State University and other places to evaluate the expected dirt holding capacity of a filter element by measuring the hydraulic pressure drop across the element. The pressure drop is then correlated with dirt holding capacity by using an experimentally derived curve of pressure drop vs. dirt capacity for a filter which meets specifications. However, the typical dirt holding capacity curve for hydraulic pressure drop is too flat in the clean filter range to effectively evaluate the condition of a filter. Sometimes it is practically impossible to distinguish between a filter that is clean and a filter having only 50% of its rated capacity available for service. Obviously, this test is grossly insufficient when reasonably accurate results are expected.

An attempt is being made currently in the Oklahoma State University Fluid Contamination Laboratories to correlate air pressure drop across a filter element with its dirt holding capacity (1). However, it has been observed that in certain filter elements, especially in the five micron (nominal) rated filters, a pressure drop measurement is not uniquely related to a particular dirt holding capacity. It is the general consensus that variations in the pore size distribution for a given element seriously effect the data and hence the results of simple air pressure drop tests. These comments should not be construed to mean that this difficulty constitutes an impasse to further development of using air flow test to evaluate hydraulic fluid filters.

According to Cranston (2), wire cloth media, as well as paper and other media, have some nonuniformity in pore size. Typical pore size distribution curves are shown in Fig. 1-3. The pore sizes vary from the smallest, to the middle size, and up to the largest. The pore size distribution curves make the probability apparent that the majority of the pores in a filter will be within some narrow mid-range in size with relatively few of the pores in the smaller and larger ranges.

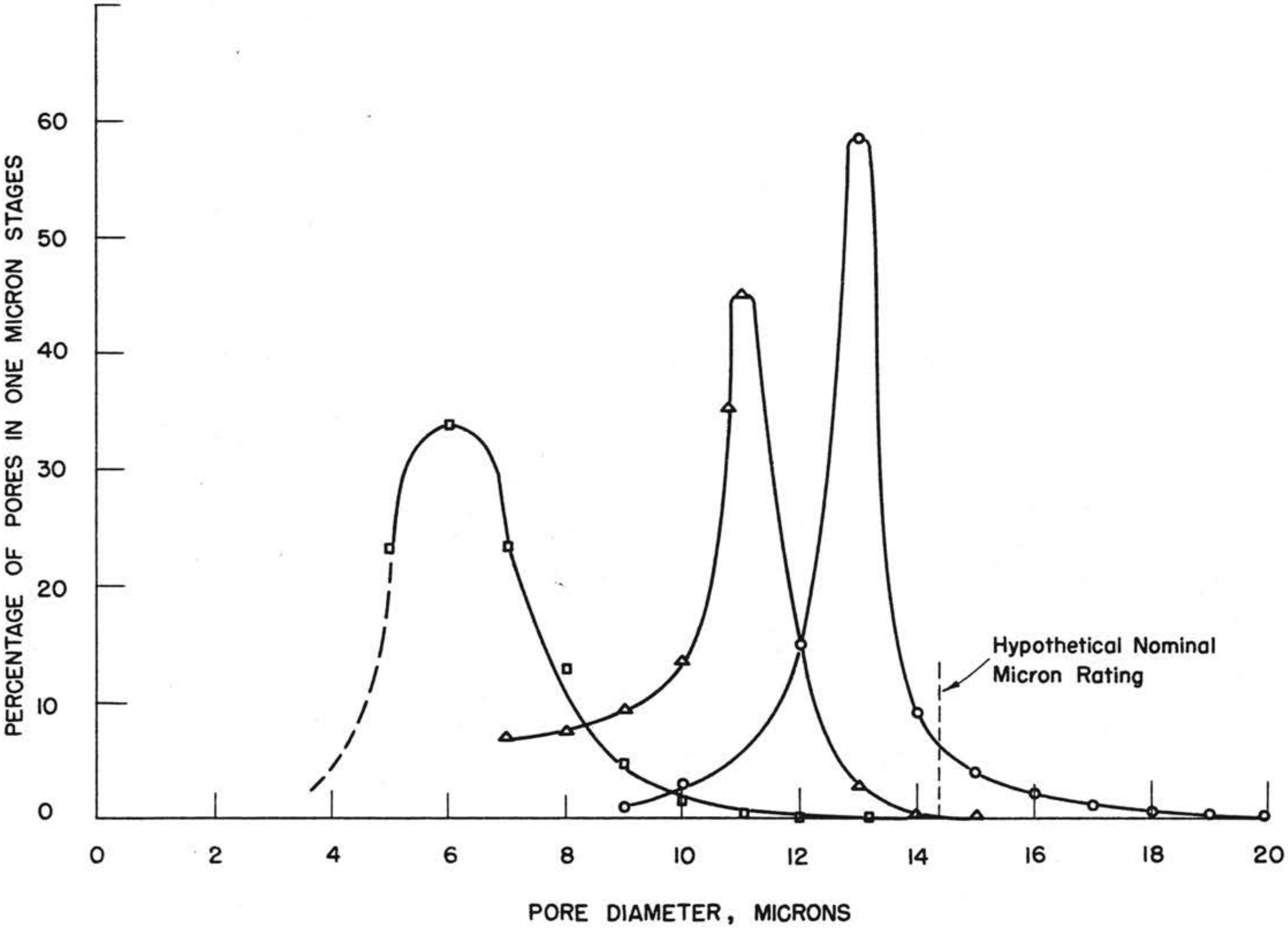


Fig. 1-3 Pore Size Distribution Curves

When a filter element is subjected to tests which are to determine its expected contamination holding capacity or other performance characteristics it is of prime interest to know the filter's mid-range pore size. Or for that matter, it is pertinent to know all one can about a filter specimen's pore size distribution. For example, pore sizes which correspond to a filter's nominal rating must necessarily be larger than the mid-range of the pore distribution. The vertical dashed line in Fig. 1-3 represents this line of reasoning. If a filter's nominal pore size is too near the size of the majority of the filter's pores, then the filter is certain to fail to meet specifications such as MIL-F-5504A and MIL-F-5504B. The same line of reasoning would apply to a hypothetical size distribution such as shown in Fig. 1-4, which exhibits a much less normal distribution than that of Fig. 1-3. Reasoning applied to other hypothetical cases point to the probable importance of pore size distribution to any filter element evaluation. Some of the difficulties that are encountered in pressure drop tests for filtering units can probably be attributed to the failure of experimental measurements to reflect the nature of the medium's interstices.

It is mentioned in the literature (3) that it is likely that the bubble-pressure method of determining a maximum pore size can be expanded to give a means of determining the pore size average of a given medium. Ludvig (4) reports only moderate success at attempts to correlate a boil point to the nominal pore size of a media. However, he states that, "This procedure was not investigated in any detail."

It is hoped that the research reported in this paper will show that the mid-range pore size of a media can be determined by a boiling-

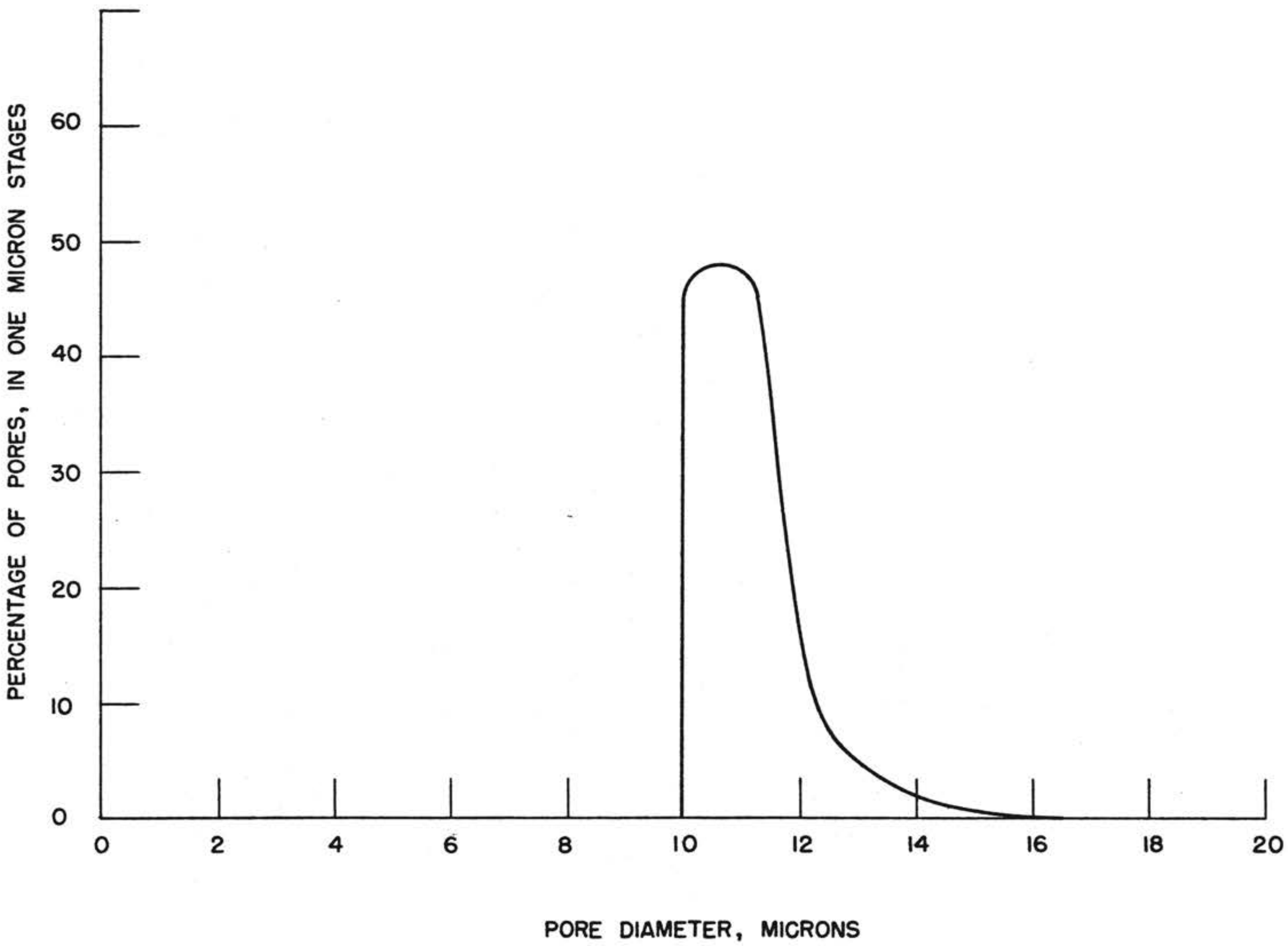


Fig. 1-4 Hypothetical Pore Size Distribution Curve

pressure test. Also, it is hoped that the boiling test results can be further correlated to dirt holding capacity through the incorporation of certain basic and empirical relations.

CHAPTER II

PREVIOUS INVESTIGATIONS

2-1 The Bubble Test Method for Determining the Maximum Pore Size

Utilization of the bubble-pressure method to measure maximum pore size is not new. Actually, it has been applied to many types of porous media such as membranes, ceramic structures, and textile fabrics. The method depends solely on a balance of forces normal to the pore opening at the outer periphery of the pore. If a circular pore is assumed, the pore diameter relation to pressure is shown by:

$$D_p = \frac{4\gamma\cos\alpha}{P} \tag{2-1}$$

Where D_p is the pore diameter, γ is the surface tension constant for the fluid used to fill the pores, α is the angle of contact between the liquid and the media surface, and P is the pressure required to overcome the surface tension of the bubble formed in the pore. If a liquid which wets the medium is chosen, the contact angle is approximately zero. Hence, $\cos\alpha$ is approximately one and can be eliminated from the equation. However, $4\gamma\cos\alpha$ is usually evaluated experimentally and the contact angle between the liquid and medium is no longer critical. Ludvig's (4) evaluation of this constant using Solox 190 is 356 where appropriate units are incorporated. The theoretical equation is reduced by inserting the experimentally arrived at value:

$$D_p \text{ (Microns)} = \frac{356}{P(\text{inches } H_2 0)} \qquad (2\text{-}2)$$

In his report, Ludvig concludes that the bubble point correlation, with accurate calibration, can be used with confidence up to at least 100 microns.

Military specification, MIL-F-5504A requires bubble point testing of filters in Solox 190 or MIL-H-5606 hydraulic fluid.

2-2 Boiling-Pressure Testing

Grace (3) mentions that the bubble-pressure method can be modified to measure the rate of air flow at various increasing pressures to arrive at a form of pore size distribution for woven media. He referenced Bechold (5), Grabar (6), and Ruemele (7) for methods of calculating pore size distribution from boiling-pressure data. Follow up on these references, in the existing Oklahoma State University Library stacks, proved to be fruitless.

The Puralator report (4) presents a graph showing a plot of nominal micron ratings, of several filters, vs. boil point micron rating, Fig. 2-1. It was concluded, by Ludvig, that this plot indicated that, "a constant factor of deviation may exist between nominal micron ratings and boil point micron ratings". That report also states that boiling-pressure measurements are readily reproducible.

Ludvig's method of designating the "boil point" is to increase flow across a three and one-half inch diameter test disk until the pressure increase is negligible with increases in flow.

The fact that bubble testing has documented accuracy in determining maximum pore sizes, along with favorable mentions in the

Paper Grade	Nominal Rating, Microns	Boil Point Correlation Microns
702	2 - 3	6
438	2 - 3	8
415	4 - 5	9.5
468	8 - 9	16
470	10	18
439	25	33
233	28	34

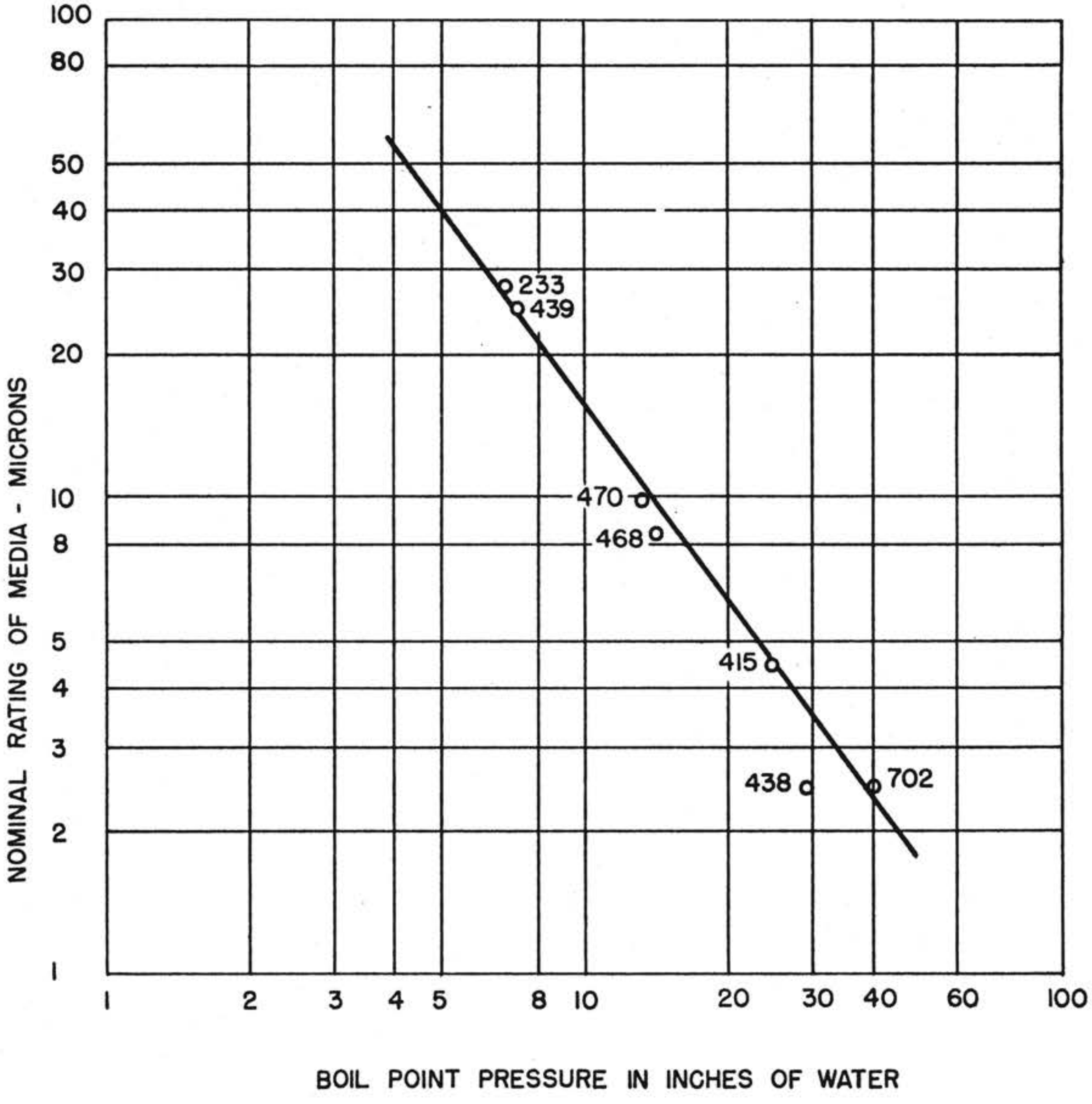


Fig. 2-1 Nominal Micron Rating vs Boil Point Micron Rating

literature of the possibilities of a boiling-pressure test for determining the "average" pore size of a filter, has led directly to the undertaking of the research reported in this thesis.

CHAPTER III

STATEMENT OF PROBLEM

Recent attempts to clean contaminated wire cloth filter elements, in order that they can be returned to dependable service, have placed justified demands for suitable methods of evaluating the elements after cleaning. Pressure drop tests with hydraulic fluid flowing through the element are not always dependable for evaluating filters. More promising results are obtained by using air as the test fluid in pressure drop tests. These tests give evidence that the interstices of elements are not adequately reflected in simple pressure drop measurements.

Since a fabricated filter element has a fixed surface area, the number of pore openings in the surface of a element must be inversly proportional to the average pore area. Carrying this line of reasoning further, if a surface type filter's dirt capacity is directly related to the number of filter pores available for plugging, then there may be a direct relationship between filter's average pore size and its dirt holding capacity.

It is recognized that the surface area of a particular filter element is fixed at the time of its manufacture, but there is much variation in surface area between filter elements of a given model. Mainly, this area variation comes from variations in the sealing of seams and end plate connections with epoxy cement.

Certain basic and emperical relations which involve area, pressure, and flow are shown in the literature (see Chapter IV). Therefore, the problem is to develop a means to measure a filter's average pore size, and then to find a means of relating that measurement to a filter's dirt holding capacity by incorporating the basic and/or empirical relationships between pressure, area and flow rate.

Since the bubble-pressure test method is known to be accurate in determining the maximum pore size of an element, it is reasoned that the boiling-pressure may suitably reflect the average pore size.

A boiling-pressure-test development has been undertaken in this study. Theoretical correlations using the average pore size, experimental data, calculated values, and the recommendations thereof, are presented in this paper.

CHAPTER IV

THEORETICAL ASPECTS

3-1 Relating Dirt Holding Capcity to Hydraulic Pressure-Drop and Pore Diameter

Flow of a viscous fluid through the weave of wire cloth filters is considered to be laminar under normal working conditions. Therefore, Poiseuille's law (8) which represents the rate of flow through a cylindrical capillary should hold. The relationship of flow rate to pressure drop, viscosity and capillary dimensions is given by the following equation:

$$Q = \frac{\pi D^4 P}{128 \mu L} \qquad (3\text{-}1)$$

This equation is appropriate for non-circular cross sections if D is suitably chosen. For example, taking the geometric mean of major and minor axial diameters for an elliptical cross section is a typical modification.

Assuming that Poiseuille's relationship will hold for a large number of parallel capillaries with the same diameter, the Eq. (3-1) can be modified by inserting the number of capillaries, N, as a factor.

$$Q = \frac{\pi D^4 PN}{128 \mu L} \qquad (3\text{-}2)$$

Considering Q, μ, and L to be constants, it is readily seen that N can be expressed as a function of pressure and the forth power of capillary diameter.

$$N = K_1 \left[\frac{1}{D^4 P}\right] \tag{3-3}$$

Theoretically Eq. (3-3) seems very promising for adaptation into an expression relating hydraulic pressure drop across wire cloth filter elements to its dirt holding capacity. Assuming that filter dirt capacity, DC, is directly proportional to the number of pores available for clogging, a direct substitution into Eq. (3-3) gives

$$DC = K_2 \left[\frac{1}{D^4 P}\right] \tag{3-4}$$

Taking the bracketed quantity of Eq. (3-4) as a single parameter related to a filter's dirt capacity, Eq. (3-4) can be modified to

$$DC = K_2 N_H \tag{3-5}$$

N_H is termed the "Hydraulic Pore Number". This theoretically derived relation has been investigated in this research by taking experimental hydraulic pressure drops, across five micron filter elements, and boiling pressure readings for values of P and D respectively. The data and results are shown and discussed in Chapters VII and VIII respectively.

The theoretical derivation and application of Eq. (3-5) is based on three major assumptions:

1. Poiseuille's law for capillary flow holds for the N capillaries of wire cloth filter elements when an average diameter is used.

2. Boiling-pressure readings are proportional to the average diameter of the filter's pores.
3. L, the capillary length, is a single value for a given filter specimen.

3-2 Relating Dirt Holding Capacity to Air Pressure Drop and Pore Diameter

Rainard's (9) empirical equation, which he proposed for correlating air-permeability data in textile fabrics is given in the form:

$$\frac{\Delta P}{Q_f} = C_1 Q_f + C_2 \qquad (3\text{-}6)$$

Rainard suggested on theoretical grounds that

$$C_1 \propto \frac{b\rho}{\pi D^2 \overline{N}^2 A^2} \qquad \text{and} \qquad C_2 \propto \frac{h\mu}{D^4 \overline{N} A}$$

For moderate air flow rates through surface filters, where h is small, and since μ is small for air, C_2 is considered negligible and Eq. (3-6) reduces to

$$\frac{P_A}{Q} = C_1 Q \qquad (3\text{-}7)$$

Examination of the denominator of the factor, C_1, shows that $D^2\overline{N}A$ represents the open pore area of the media. Assuming that b, $\overline{N}A$, ρ, and Q are constant in this application, Eq. (3-7) can be expressed in the form.

$$P_A = C_3 \frac{1}{D^2 N^2} \qquad (3\text{-}8)$$

Rearranging Eq. (3-8), and including the additional assumption that a filter's dirt capacity, DC, is directly proportional to the number of open pores, N, gives

$$DC = C_4 \left[\frac{1}{D^2 P_A} \right]^{1/2} \qquad (3\text{-}9)$$

As in Eq. (3-5), the bracketed quantity is taken as a single parameter to give

$$DC = C_4 N_A \qquad (3\text{-}10)$$

Here, N_A is termed the "Air Pore Number".

The theoretically derived relation has been investigated in this research by taking experimental air pressure drops and boiling-pressure readings for values of P_A and D respectively. The data and results are shown and discussed in Chapters VII and VIII.

CHAPTER V

REQUIREMENTS ON THE DESIGN OF APPARATUS

Bubble pressure tests and boiling pressure tests of filter elements require that the test specimens be submerged horizontally to a depth of one-half of an inch below the free surface of the fluid which is used in the test tank. Since the test requires visual inspection, the test tank should be transparent to permit a better view of the specimen. For the same reason, adequate lighting must be provided.

During the actual testing of an element, the specimen must be rotated. Therefore,a mounting spindle which will permit rotation as air is forced into the filter core should be provided.

Depending on the fluid used in the apparatus (alcohol is used sometimes) certain safety precautions should be built into a bubble-test stand. For example, a means to drain the test tank, without handling the tank itself, provides a means of safely removing the fluid in the event of a fire. Along the same line of reasoning, space for storing the fluid should be provided for in the stand.

The Oklahoma State University bubble-test stand is illustrated in Fig. 5-1. The cabinet space of this stand (located in the rear of the stand) is not shown in the figure. Inclusion of cabinet space in the illustrated stand has proven to be very practical from the standpoint of convenience and safety for storing the alcohol which is used

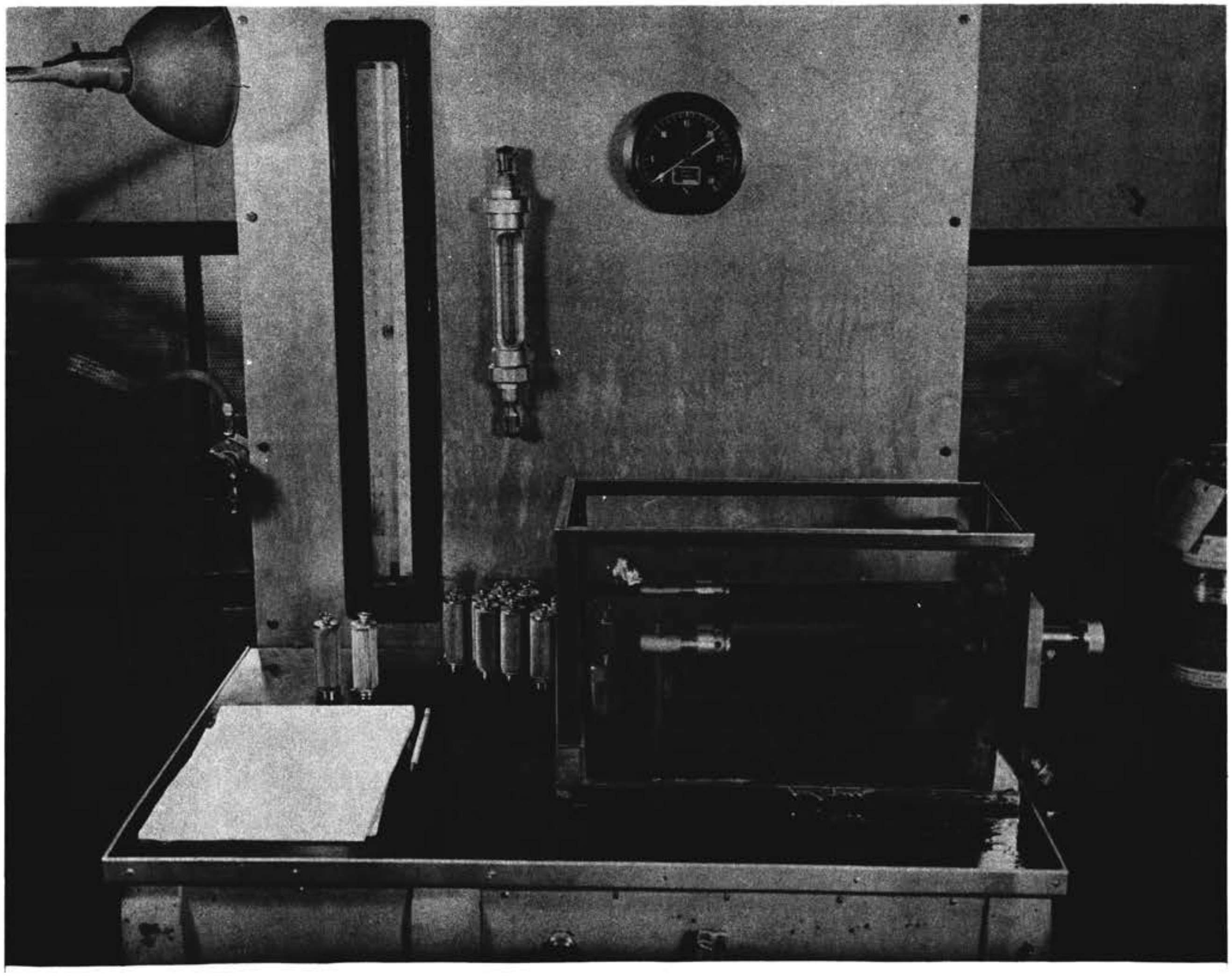


Fig. 5-1 Oklahoma State University Bubble Test Stand

in the testing tank. The drain line from the extreme right hand lower part of the tank leads directly to the storage receptical located in the cabinet space.

Fig. 5-2, is a diagram showing the typical connections of the various instruments or gages incorporated in the stand. The Rotameter is necessary only when the stand is to be used for boiling-pressure measurements.

Fig. 5-3(a) illustrates the important details of the filter elements mounting spindle for the bubble-test stand and Fig. 5-3(b) shows the only modifications required of the pressure gage connection for boiling-pressure tests. The assembly drawing of the spindle is adequate for a construction guide. Actual dimensions of parts in a stand of this type are dependent on the dimensions and physical configurations of the filter elements which are to be tested on the stand. For this reason the dimensions are not given here. The ranges of the instruments used in the Oklahoma State University stand are given in Appendix B.

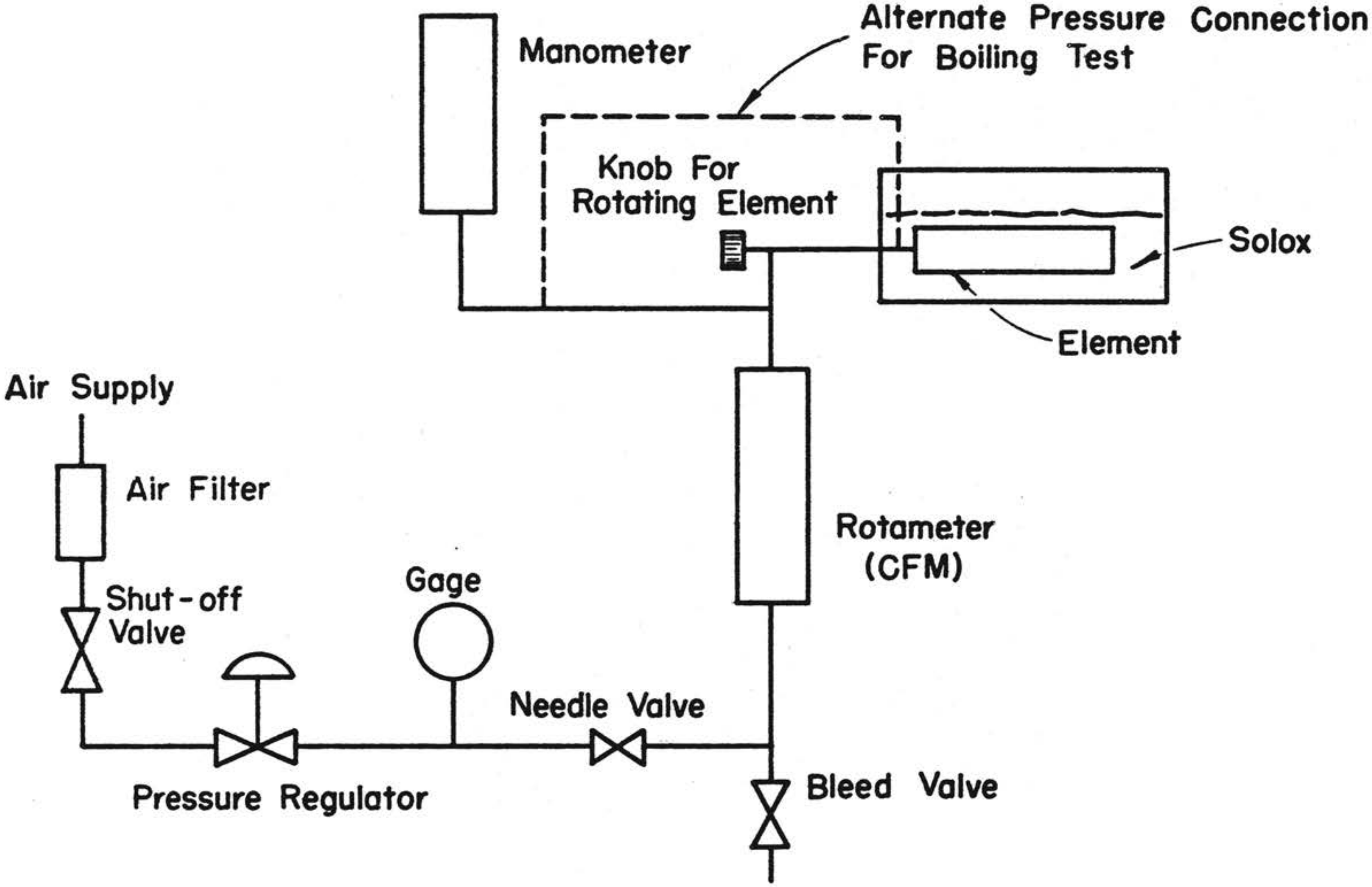
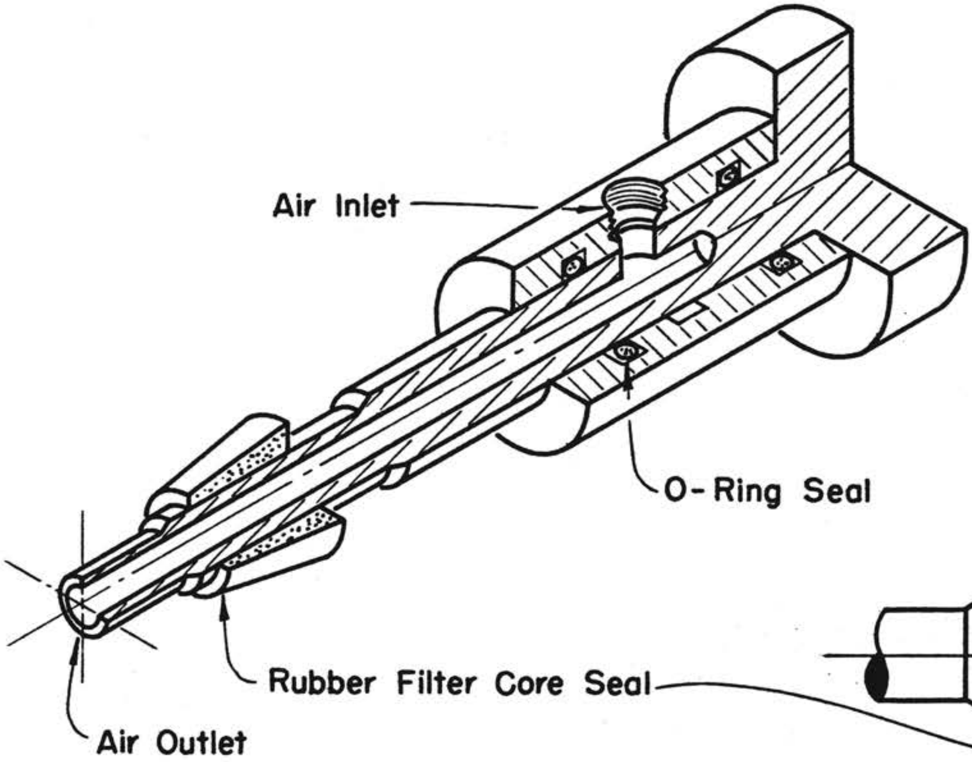
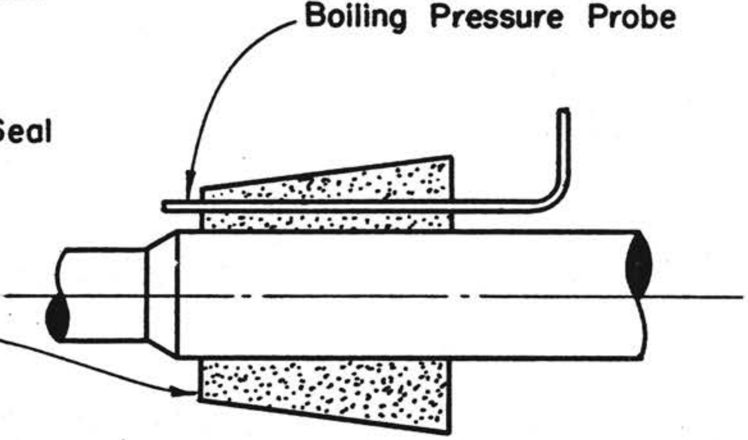


Fig. 5-2 Diagram of Oklahoma State University Bubble Test Circuit



(a)

Fig. 5-3 Filter Element Mounting Spindle
(a)



(b)

Fig. 5-3 Modification Incorporated for
(b) Boiling Test

CHAPTER VI

SUPPORT EQUIPMENT

6-1 Determination of Dirt Holding Capacity

Dirt holding capacity tests are conducted with an artificial-contaminant loading stand, Fig. 6-1. This equipment was designed and fabricated by Oklahoma State University personnel.

Fig. 6-2 shows a flow diagram of the stand. There are several flow paths which can be selected to satisfy special test procedure requirements. Four-way valves, A and B, are used to route the fluid where it may:

a. Flow from the pump through the test run and back to the reservoir.
b. Flow from the pump through the control filter, through the test run, and back to the reservoir.
c. Flow from the pump through the control filter and back to the reservoir.
d. Flow from the pump and completely bypass the control filter and the test run.

Some additional features of the dirt loading system are: The main stand is equipped with a forty gallons per minute pump which is driven by a seven and one-half horsepower varidrive unit. A conicol reservoir is used to eliminate dirt traps which are inherent in

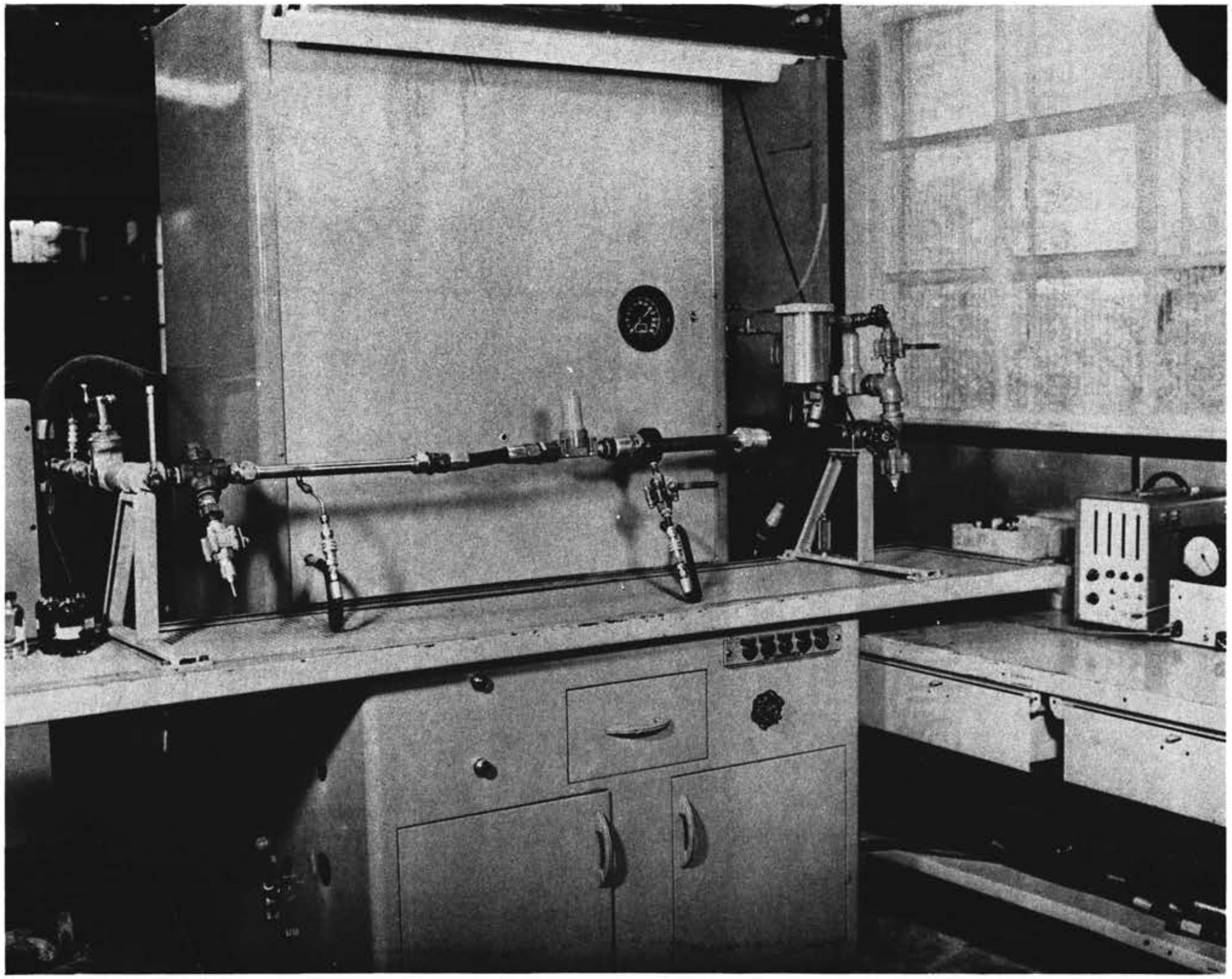


Fig. 6-1 Artificial Contaminant Loading Stand

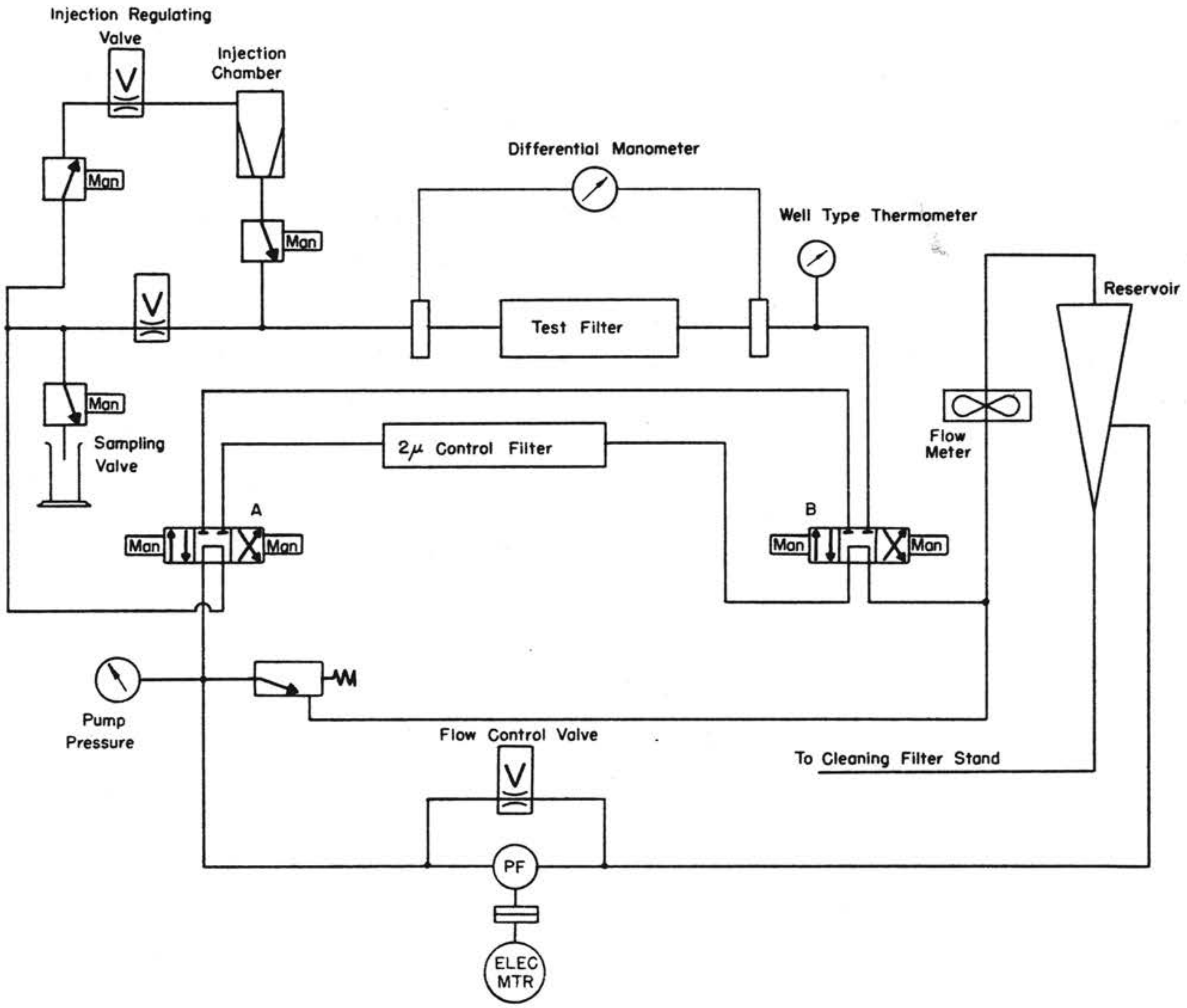


Fig. 6-2 Flow Diagram for Loading Stand

rectangular reservoirs. A two micron "absolute" control filter is installed to insure that clean fluid circulates through the test run.

An auxiliary clean-up stand is also connected to the conical reservoir. This stand features a hydroclone unit which effectively controls the contaminant level of the system. The hydroclone, which was designed and built by Oklahoma State University personnel, is essentially a centrifugal device which separates contaminant particles from the hydraulic fluid.

Fluid flow rate through the test run is measured with a Fischer-Porter turbine meter. This device is accurate to .05 percent over a range of three to forty-five gallons per minute. The output of this meter is "fed" into a Hewlit-Packard electronic counter which displays a digital read out.

Differential pressure connections, across the test filter unit, are made with a Wallace and Tiernan pressure gage.

Fluid temperature is held constant throughout a contaminant capacity test. Saybolt viscosity checks are made periodically to insure that tests are conducted at a specified viscosity.

AC fine test dust is used as the contaminant for determining the dirt holding capacity of filter elements, in accordance with military specification MIL-F-5504A. Contaminants are accurately weighed on an analytical balance and are injected into the test run, upstream of the filter, in a slurry of test dust and hydraulic fluid. Control of injection rate is accomplished by the injection regulating valve, Fig. 6-2.

The complete sequence of a typical test is as follows:

a. Filter housing pressure drop (tare pressure) is determined before an element is installed in the housing.

b. The filter is installed in its housing for the initial filter pressure drop reading.

c. A portion of fluid is routed through the contaminant injection chamber for one and one-half minutes. However, it has been determined that the major part of the contaminant slurry is injected during the first thirty seconds of this period.

d. The pressure drop reading is taken one minute after the injection chamber is closed out of the test run. This allows time for equilibrium conditions to be reached.

e. The above steps are then repeated until the filter bypass relief pressure is reached (the filter bypass valve is usually blocked for this test).

All of the pressure readings and injections for this test are made with flow rate and temperature maintained at specified levels. The amount of contaminant required to produce relief valve opening pressure is termed the dirt holding capacity of the filter. Fig. 6-3 shows typical curves for dirt holding capacity determination.

6-2 Contamination Level Laboratory

The Oklahoma State University Fluid Contamination Laboratory has an auxiliary laboratory where fluid contamination levels are determined. This laboratory is fully equipped to analyze the contaminant content of hydraulic fluid samples. For example, the fluid in the dirt loading system is periodically examined for its contamination content. Gravimetric analyses are performed for quantitative information.

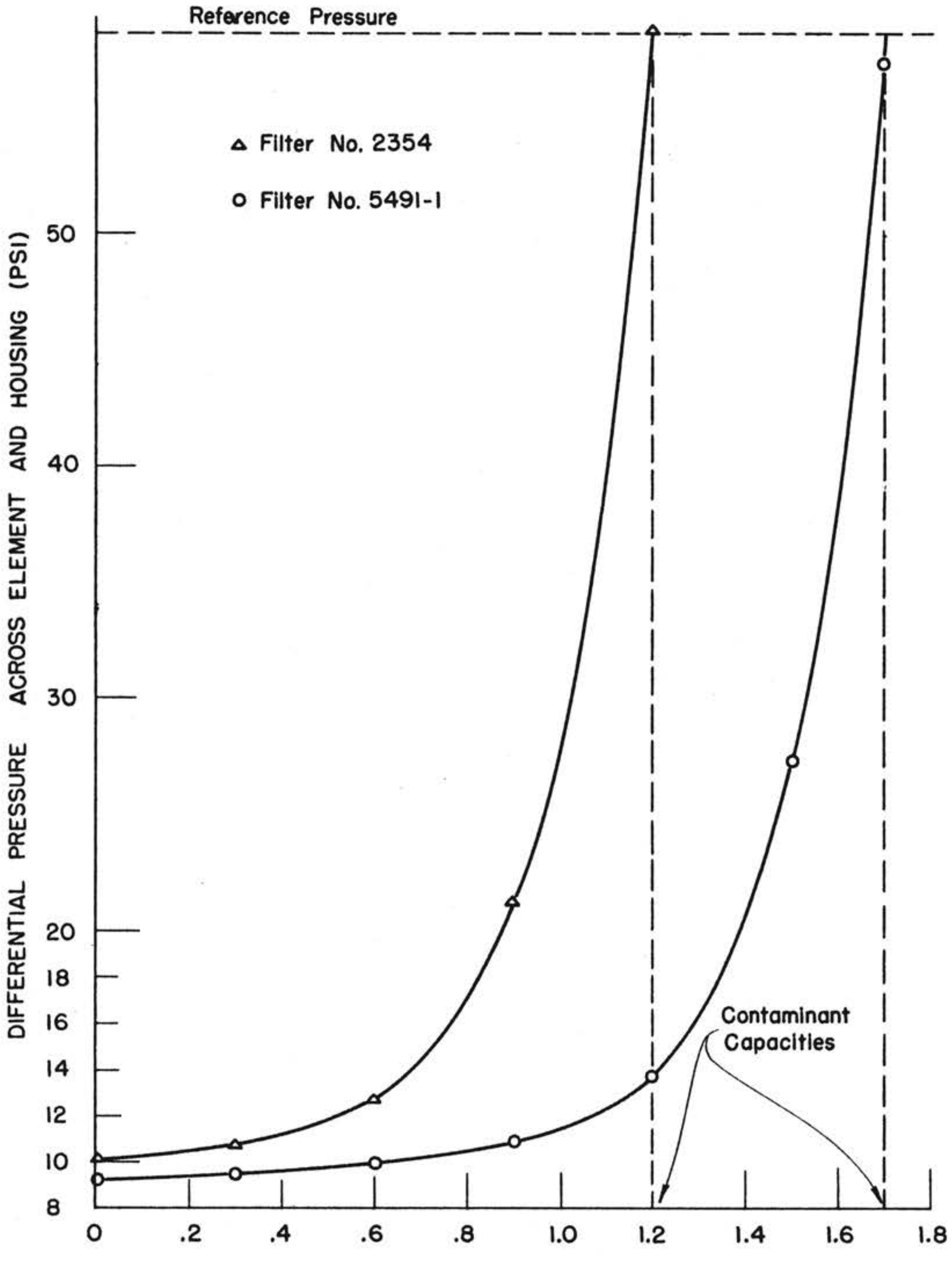


Fig. 6-3 Typical Curves for Determining Dirt Holding Capacity

Microscopic counts and/or Coulter Particle Counter electronic counts are made for qualitative and quantitative information.

Equipment for the analysis of contaminant in hydraulic fluid specimens is located in an isolated clean-room. This room is provided with a clean, temperature controlled atmosphere by a Westinghouse "Precipitron" unit and an air conditioning unit respectively. The results of fluid analyses can be greatly affected by dirty ambient conditions.

Microscopic analysis provides a relatively fast means of checking a sample qualitatively. However, it is difficult, if not impossible, to make a particle count where the contamination level is anything except very low. Particle sizes are determined with a special micrometer stage eyepiece mounted on the microscope.

The electronic Coulter Particle Counter is an important feature in the equipment of the contamination laboratory. Fluid samples which have particles numbering in the tens or even hundreds of thousands per five-hundred micro liters can not be analyzed with the microscope. However, the Coulter Particle Counter can accurately (counts repeat, within two-thirds the square root of the average count for any specified diameter of particle contamination) count the particles in a selected size range in a few minutes. This equipment allows fast quantitative and qualitative analyses of fluid samples.

Gravimetric analysis of a fluid is accomplished by passing the fluid sample of known volume through a .45 micron "Millipore" filter. The "Millipore" filter disk is then placed in an oven to drive off all fluid residue. Weighing of the filter disk and contaminant on an analytical balance gives a gross measurement. Net contaminant weight per unit volume is calculated by subtracting the tare weight of the filter disk.

CHAPTER VII

DATA AND RELATED ILLUSTRATIONS

Table 7-1 presents the experimental data from bubble-pressure and boiling-pressure tests of five-micron (nominal) wire cloth filter elements.

Table 7-2 presents calculated values, of maximum pore diameters and "average" pore diameters, using Eq. (2-1). The values which are listed in Table 7-2 are based on an experimental evaluation of the numerator of Eq. (2-1). It was determined from Coulter Particle Counter evaluation of the maximum particle size to pass through a selected filter element, at rated hydraulic flow, that $4\gamma\cos\alpha = 240$. The fluid used in the bubble-pressure and boiling-pressure apparatus was a solution of "absolute" ethyl alcohol, and MIL-H-5606 petroleum base hydraulic fluid. This evaluation is very near to a similar evaluation quoted in the Puralator report (4) where denatured ethyl alcohol was used. Their evaluation was: $4\gamma\cos\alpha = 238$.

Table 7-3 presents data from hydraulic pressure-drop tests at rated flow, air pressure-drop tests, and actual dirt capacity (ADC) determinations using AC fine test dust.

Table 7-4 presents values of N_H and N_A which were calculated from values listed in Tables 7-2 and 7-3.

Fig. 7-1 shows points plotted for "Hydraulic Pore Number",

TABLE 7-1

DATE FROM BUBBLE TEST AND BOILING TEST
OF FIVE-MICRON FILTER ELEMENTS

Filter No.	Bubble Pressure (in. H_20)	Boil Pressure (in. H_20)
A-155	14.9	18.5
A-256	15.0	18.0
2354	16.1	17.8
2811	14.8	19.0
2987	15.5	18.1
3023	14.9	17.4
4752	13.4	17.5
5303	14.9	17.8
5508	14.1	17.9
5491	15.6	17.4
5586	16.5	17.3
5711	14.1	18.1
5955	15.3	17.6
10329	15.6	17.5
10927	13.4	18.2

(Filters Manufactured by Aircraft Porous Media, Inc., Part No. AC-730-E8)

TABLE 7-2

CALCULATED VALUES FROM BUBBLE PRESSURE AND BOILING PRESSURE EXPERIMENTS

Filter No.	Maximum Pore Size (Microns)	Average Pore Size (Microns)
A-155	16.1	13.0
A-256	16.0	13.3
2354	14.9	13.5
2811	16.2	12.6
2987	15.5	13.3
3023	16.1	13.8
4752	17.9	13.7
5303	16.1	13.5
5508	17.0	13.4
5491	15.4	13.8
5586	14.5	13.9
5711	17.0	13.3
5955	15.7	13.6
10329	15.4	13.7
10972	17.9	13.2

TABLE 7-3

DATA FROM HYDRAULIC PRESS DROP, AIR PRESSURE DROP AND DIRT CAPACITY EXPERIMENTS

Filter No.	Hydraulic Press. Drop (PSI)	Air Press. Drop (in. H_20)	Dirt Capacity (Grams)
A-155	1.00	1.488	1.41
A-256	1.20	1.515	1.39
2354	1.60	1.681	1.20
2811	1.45	1.665	1.37
2987	1.20	1.570	1.61
3023	1.20	1.594	1.30
4752	1.55	1.656	1.20
5303	1.25	1.620	1.46
5508	1.00	1.499	1.62
5491	1.10	1.538	1.39
5586	1.35	1.609	1.54
5711	.95	1.491	1.51
5955	1.30	1.651	1.44
10329	.75	1.456	1.72
10972	1.10	1.529	1.54

TABLE 7-4

CALCULATED VALUES OF N_H AND N_A

Filter No.	$N_A \times 10^2$	$N_H \times 10^4$
A-155	.398	.350
A-256	.373	.267
2354	.326	.188
2811	.378	.273
2987	.360	.267
3023	.304	.229
4752	.322	.183
5303	.339	.239
5508	.372	.309
5491	.342	.250
5586	.322	.198
5711	.379	.337
5955	.328	.225
10329	.327	.377
10927	.334	.300

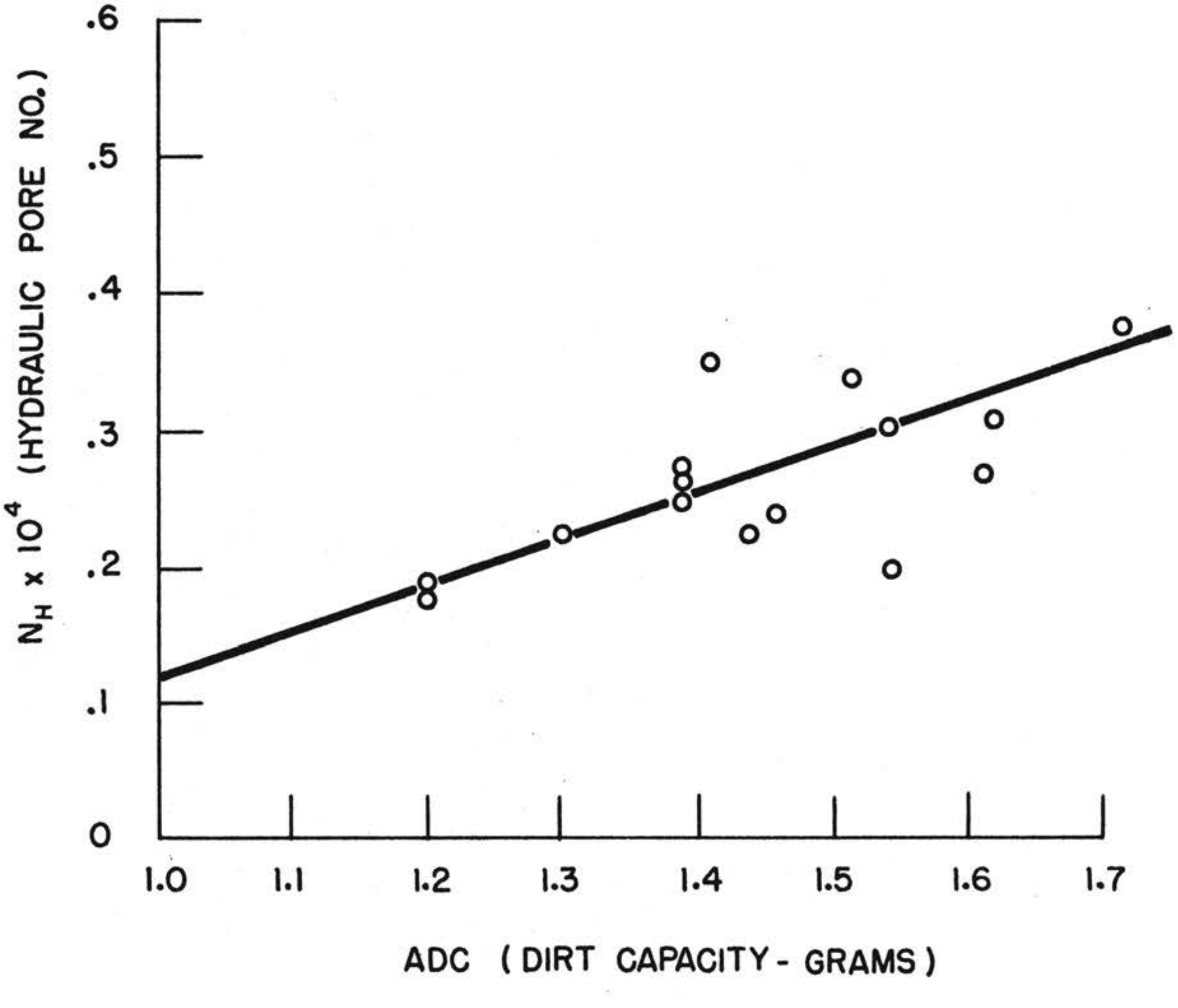


Fig. 7-1 "Hydraulic Pore Number", N_H, vs ADC (Actual Dirt Holding Capacity)

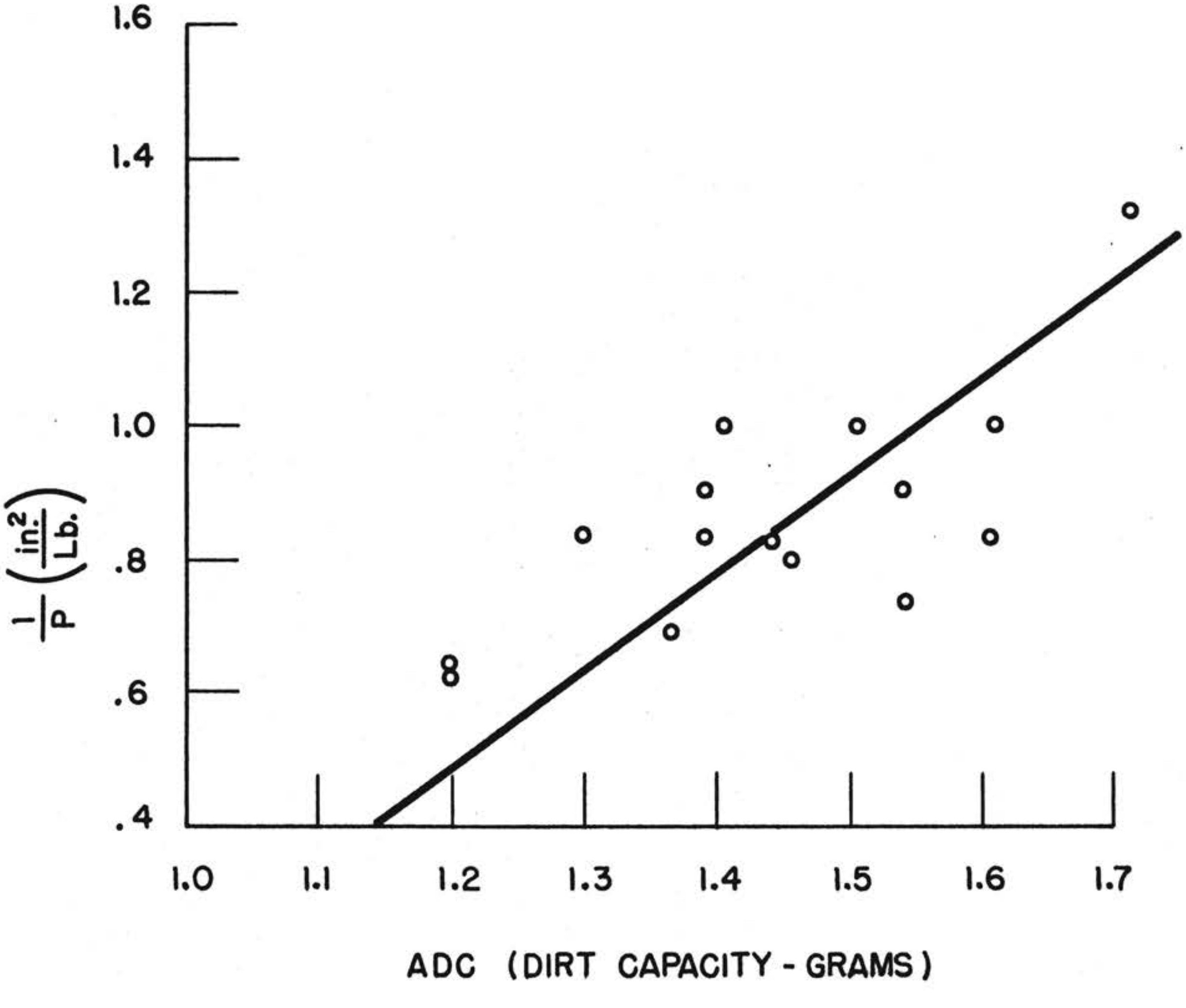


Fig. 7-2 Inverse of Hydraulic Pressure Drop, 1/P, vs ADC

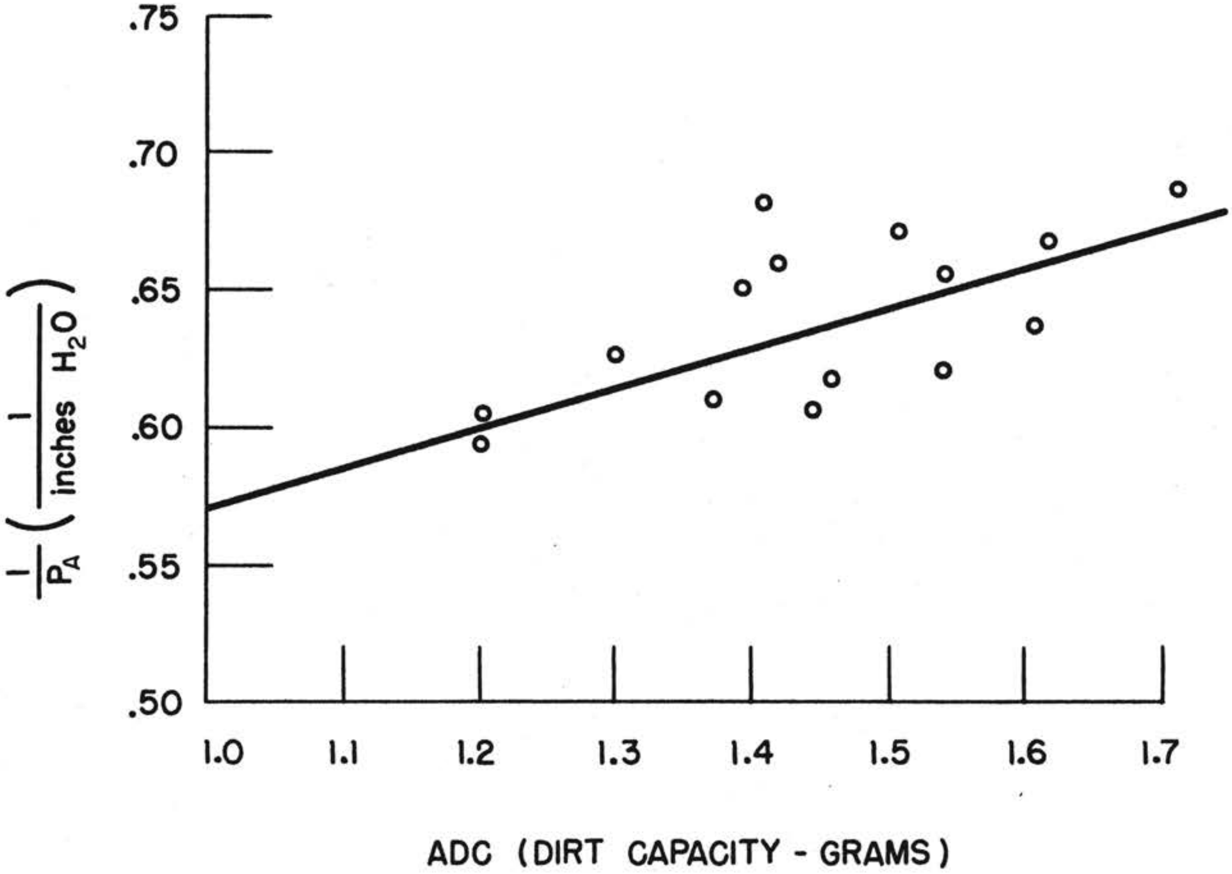


Fig. 7-3 Inverse of Air-Pressure Drop, $1/P_A$, vs ADC

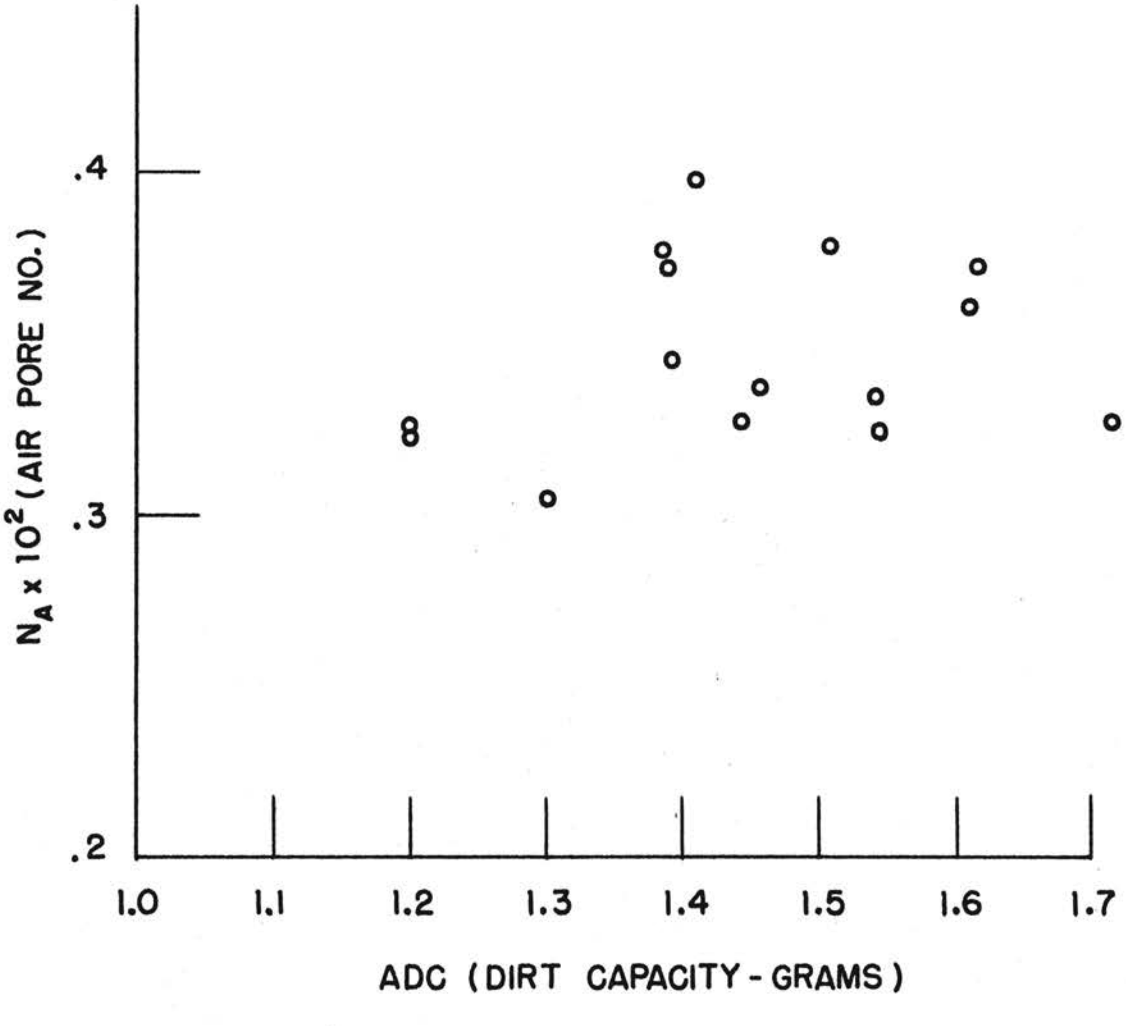


Fig. 7-4 "Air Pore Number", N_A, vs ADC

N_H, vs ADC (Actual Dirt Holding Capacity). The solid line is arbitrarily drawn in as an aid in visualizing the point distribution.

Fig. 7-2 shows points plotted for the inverse of hydraulic pressure-drop, $1/P$, vs ADC. The solid line in the figure is also arbitrarily drawn in as an aid in visualizing the point distribution. A comparison of Fig. 7-1 and Fig. 7-2 is included in Chapter VIII.

Fig. 7-3 shows points, with a line arbitrarily drawn in, for $1/P_A$ plotted against ADC. A similar plot of N_A vs ADC is presented in Fig. 7-4. No line has been drawn in Fig. 7-4 because of the complete absence of a pattern which a straight line might be drawn through and offer some clarification. Discussion of Figs. 7-3 and 7-4 is also included in Chapter VIII.

CHAPTER VIII

DISCUSSION OF RESULTS, CONCLUSIONS, AND RECOMMENDATIONS

8-1 Discussion of Results

According to previous reasonings applied to pore size distribution in Chapter I, the calculated values of "average" pore diameters (Table 7-2) are greater than what is probable for filter elements which have a five-micron (nominal) rating. The average pore size of the tested filters, with a normal distribution assumed, is more likely to be near two or three microns rather than the calculated values which range near thirteen microns. However, Aircraft Porous Media, Inc. reports that the surface indentions in the Dutch twill weave media will accomodate glass beads which are thirteen microns in diameter. From this, it is concluded that the boiling-pressure tests did not measure the smaller internal pores of the wire cloth; but, it did with reasonable accuracy, measure the surface indentions of the media. This conclusion is reasonable since the bubbles are actually formed in the surface indentions. Attempts to increase the pressure, above those which are recorded in Table 7-1, failed because the increased air flow rate created a separation between the filter and the test fluid. When separation occurs, there is a sudden loss of pressure and an increase in flow.

Since the size of the internal pores of the media are likely to be directly related to the size of the indentions (both are dependent on the wire size) it is concluded that the oversized measurements suitably reflect a relative pore size distribution for inclusion in the theoretical relations which were derived in Chapter IV.

With the exception of two points, the point distribution of Fig. 7-1 is distinctly improved over that of Fig. 7-2. This is taken as sufficient evidence to conclude at this time that pore size should be included in future correlation attempts between dirt capacity and hydraulic pressure drops. Although the limited number of attempts, which are represented in the data, do not permit a definite conclusion as to verifying or to disproving the theoretically derived relation of Eq. (3-5), the writer should like to express confidence that there is some validity in the approach. It should be noted here that actual dirt capacity correlations with the theoretical parameter, N_H, will probably demand an additional constant term. That is, if the arbitrarily drawn line of Fig. 7-1 has significance. This would modify the theoretical relation, Eq. (3-5), to:

$$DC = K_2 N_H + K_3 \tag{8-1}$$

No attempts have been made, in this research, to evaluate the constants of Eq. (8-1).

Comparison of Fig. 7-3 and Fig. 7-4 offers no basis for any verification of the theoretically derived relationship of Eq. (3-10). However, the air pressure-drop data included in this thesis are calculated from extrapolated values from logarithmic graphs of experimental data for $\mathrm{Ln}\, P_A = C\, \mathrm{Ln}\, Q_A + C'$ for the particular filter elements.

The extrapolated values were used because they corresponded to low flow rates. It is very possible that the air pressure values that were used are not realistic for inclusion in the derived relation, Eq. (3-10). Further study is indicated before conclusions can be made.

8-2 Summary of Conclusions

The writer's conclusions are summarized in the following list.

1. The boiling-pressure test can be used to accurately measure the size of the surface indentions of wire cloth filter media. The surface indentions may or may not be the same size as more internal openings in the weave.
2. If the indention size is directly related to the internal pore size, that measurement can be suitably employed in Eq. (3-5).
3. There is definite promise that the theoretical relation of Eq. (3-5) or Eq. (8-1) can be verified by further experimentation.

8-3 Recommendations for Future Study

Before stronger conclusions can be made, concerning dirt capacity correlation with N_H and N_A values, further study is indicated. Fig. 7-2 illustrates the futility of correlating simple hydraulic pressure-drop with dirt capacity. But, Fig. 7-1 offers definite encouragement for future study towards the adaptation of the boiling-pressure test results in dirt capacity correlations.

It is recommended that future study of the boiling test be made toward a method of calibrating the boiling-pressure apparatus to other types of weaves by using sized glass beads.

It is recommended that future study of the boiling test, and verification attempts of the theoretical relationships of Eqs. (3-5) and

(3-10) should be made with less complex media specimens than fabricated filter elements. A more basic study with simple configurations of filter media is definitely indicated.

It has been observed that some of the artificial contaminant, that is accredited to a filter's dirt holding capacity, actually passes through the filter. It is recommended that this mis-accreditation be investigated to determine how this affects dirt holding correlations. It may be that a more homogeneous artificial contaminant must be used before dependable correlations can be made.

A SELECTED BIBLIOGRAPHY

1. Tucker, R. H., "The Development of a Method to Predict the Contamination Capacities of Low Micron, Woven Stainless Steel Filter Elements," M. S. Thesis, Oklahoma State University Library, Stillwater, 1962.
2. Cranston, R. W., "The Filtration of Fine Particles," Aircraft Engineering, Vol. 24, June, 1952.
3. Grace, H. P., "Structure and Performance of Filter Media," American Institute of Chemical Engineers, Vol. 29, Sept., 1956, pp. 307-360.
4. Ludvig, E., "Evaluation of Filter Media," Report No. 2633, Puralator Products, Inc., 970 New Brunswick Ave., Rahway, N. J., March 23, 1960.
5. Bechhold, H., Z. physik. Chem., Vol. 64, 1908, p. 328.
6. Grabar, P., and Nikitine, J., Journal of Chemistry and Physics, Vol. 33, 1936, p. 721.
7. Ruemele, T., Z. Anal. Chem., Vol. 119, 1940, p. 360.
8. Binder, R. C., Fluid Mechanics, Prentice-Hall Inc., Englewood Cliffs, N. J., 1955.
9. Rainard, L. W., Textile Research Journal, Vol. 17, 1947, p. 167.

APPENDIX A

Operating Procedures

Bubble tests to determine the maximum pore size should be conducted in the following sequence:

1. Install the filter element, which is to be tested, on the filter mounting spindle, Fig. 5-3(a). The installed element must be horizontal. The level of the test fluid (Solox 190) should be one-half of an inch above the top of the filter element and held constant throughout the test.
2. Set the air regulator pressure, Fig. 5-2, to approximately six inches of water above the calculated bubble point pressure according to the absolute rating of the filter element.
3. Open the needle valve and allow the air pressure in the filter core to increase and slowly displace the fluid in the filter core. The spindle should be rotated as the pressure is increased. The pressure reading corresponding to the first few bubbles should be noted as the approximate pressure for subsequent readings. The location, of the first pore to bubble, should also be determined at this time. It may be necessary to repeat this step several times to insure the location of the first pore to bubble.
4. Stop rotating the spindle with the pore location of step three

at a uppermost level with respect to the test fluid's free surface.

5. Prepare for all final readings by closing the needle valve and allowing the air in the filter core to escape through the bleed valve.
6. Open the needle valve and carefully allow air to flow into the filter core until a pressure of one inch of water below the approximate pressure of step three is reached. From this point, pressure should be increased in increments of one-tenth of an inch of water until continuous bubbling from the previously located pore of step four is achieved. The corresponding pressure for continuous bubbling is taken as the bubble point pressure for the maximum pore size.
7. Steps five and six should be repeated three times and the average of the bubble point pressures is taken for pore size calculations.

Boiling-pressure tests are made with essentially the same apparatus as the bubble pressure tests. The only modifications being that a pressure probe is inserted in the filter core, Fig. 5-3(b), for the boiling test. The difference being that the bubble pressure test is static (no flow) where the boiling test is made at a specific flow rate. The desired flow rate is determined experimentally by increasing the flow until pressure changes become negligible with changes in flow. All tests are made at the same flow rate.

The procedure sequence for boiling pressure determination is as follows:

1. Install the filter element, which is to be tested, on the filter mounting spindle. The element should be horizontal, with the free surface of the test fluid (Solox 190) one-half of an inch above the top of the filter element.
2. A satisfactory air regulator setting is determined experimentally. Set the regulator such that it will allow the desired air flow rates with adjustments of the needle valve.
3. Boiling pressure readings are always taken at the termination of increasing the flow to the desired rate. Never take this reading after decreasing flow adjustments have been made. Allow pressure equilibrium to be reached before taking the pressure reading.
4. After each boiling pressure test, close the needle valve and open the bleed valve to release any air pressure in the filter core until bubbling stops.
5. Repeat this test until three identical readings are achieved.

APPENDIX B

Component List of Test Stand

The following components are incorporated in the fabrication of the Oklahoma State University bubble test stand.

Description	No. Required
1. Five gallon rectangular acquarium with mounting spindle	1
2. Air pressure regulator, Press. range: 0-30 psi.	1
3. One-fourth inch (NPT) needle valve	1
4. Rota-meter, Flow range:	1
5. Pressure gage, Range: 0-30 psi.	1
6. Well-type manometer, Range: 0-20 inches H_20	1

APPENDIX C

LIST OF SYMBOLS

A	Surface area of filter medium, sq. in.
b	Empirical constant in Rainard's Eq. (3-5) dimensionless
C_1	Constant of proportionality Eq. (3-7)
C_2	Viscous coefficient in Rainard's Eq. (3-6) gm sec per cm^5
C_3	Constant of proportionality Eq. (3-8)
C_4	Constant of proportionality Eq. (3-10)
D_p	Pore diameter microns
DC	Dirt capacity, gms.
D	Diameter of capillary, in.
h	Effective pore length, cm.
K_1	Constant of proportionality Eq. (3-3)
K_2	Constant of proportionality Eq. (3-4)
L	Length of capillary, in.
N	Number of pores in a filter element, pores
$\overline{N}$	Number of pores per unit area, per sq. cm.
N_a	Air pore number, in. H_2O - sq. microns
N_h	Hydraulic pore number, sq. in. per lb. - $microns^4$
P_a	Air pressure drop, in. H_2O
P_b	Bubble pressure drop, in. H_2O
P	Hydraulic pressure drop, lb per sq. in.

ΔP	Pressure drop across medium with single fluid phase flowing, lb. per sq. in.
Q	Volume flow rate, cu. in. per sec.
Q_f	Rate fluid flow through filter medium, cc per sec.
α	Alpha, Contact angle, degrees
γ	Gamma, Surface tension, lb. per in.
μ	Mu, Fluid Viscosity, lb-sec per sq. in.
μ_1	Mu, Fluid Viscosity, centapoises

VITA

Robert Ernest Reed

Candidate for the Degree of

Master of Science

Thesis: INITIAL DEVELOPMENT OF A BOILING-PRESSURE TEST FOR WIRE CLOTH FILTER ELEMENTS

Major Field: Mechanical Engineering

Biographical:

Personal Data: Born October 11. 1927, in Vicksburg, Mississippi, the son of Jesse and Vivian Reed.

Education: Graduated from Carr Central High School, Vicksburg, Mississippi, class of 1945; received the degree of Bachelor of Science in Mechanical Engineering at Mississippi State University, May, 1960; completed the requirements for the Master of Science degree in August, 1962.

Experience: Employed as an Instructor, Mechanical Engineering, Mississippi State University, September, 1960 through May, 1961. Employed as Research Associate, Ceramic Engineering Department, Mississippi State University, June, 1961 through August, 1961. Employed as Research Assistant, Oklahoma State University, September, 1961 to September, 1962.

Professional Organizations: Associate member of the American Society of Mechanical Engineers. Member of the American Society of Engineering Educators. Engineer-In-Training, State of Mississippi.

Honorary Organizations and Awards: Pi Tau Sigma, Phi Kappa Phi, Tau Beta Pi, Who's Who Among Students in American Universities and Colleges, 1959-1960.