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Doctor's Dissertation

**A Study of the Relationship between Air Permeability
and Oil Permeability of Paper**

by William Hugh Lane

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**A STUDY OF THE RELATIONSHIP BETWEEN AIR PERMEABILITY
AND
OIL PERMEABILITY OF PAPER**

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EDITORIAL OFFICE

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INTRODUCTION

This study was undertaken in the hope that it might illuminate the many interesting conjectures regarding the mechanism of the flow of printing ink into paper during the printing process. From one point of view there are two limiting conditions of interest: the flow of ink without external pressure under capillary forces alone, and the flow of ink under external pressures so high as to make the surface tension forces negligible. Laroque (19) supports the view that the flow of ink under high external pressures is so great as to make the flow due to surface tension forces negligible. He found that the capillary pressure which is responsible for the absorption of the printing oil by the paper amounted to but 1.6 lb. per sq. in. in the case of a S. O. book paper and 1.0 lb. per sq. in. in the case of a bond paper. Although these pressures are very small in comparison with the actual printing pressures which may range up to 750 lb. per sq. in., it must be remembered that the actual printing pressure acts for only a fraction of a second, whereas the capillary forces may act for many times this long. It is commonly thought that the actual printing pressures predominate during the printing impression, while the capillary forces predominate during the drying period which follows. Any appreciable flow following the impression is undesirable as it tends to diffuse the printed image; the rheological properties of the ink are controlled to minimize such flow. The depth to which the ink penetrates the sheet is of importance. If the penetration is negligible

the ink pigment may not be satisfactorily bound to the sheet, and the ink may not dry properly. If the penetration is considerable, excessive amounts of ink may be required, show-through may be emphasized, and the printed image may be dull and chalky. Among the conjectures regarding the flow of ink into paper are those dealing with the pressure actually effective during the printing impression. In a large "solid black" the hydrostatic pressure in the ink may be the same as the pressure of impression--i. e., the pressure between printing form and paper. During the very short interval of the impression, the ink cannot escape laterally and must bear what is essentially the pressure of impression. On the other hand, under a half-tone dot, the ink may flow laterally rapidly enough to reduce the effective pressure considerably below the pressure of impression.

When the flow of ink into the sheet takes place under high pressures, the wettability of the sheet by the ink vehicle is not an important variable; when the flow takes place under capillary forces alone, the wettability of the sheet is an important variable, unless all papers are completely wet by the vehicle of all printing inks. Many technical men believe that the wettability of paper by the vehicles of ordinary ink is not a variable in the penetration process. If wettability is not a variable in the process, the rate of penetration of oils and ink vehicles into paper should be determined by the pore sizes and their distribution in the sheet, the viscosity and the surface tension of the liquid, and the pressure difference driving the oil or vehicle into the sheet. In that case, the ranking of a group of papers by rate of oil penetration should be the same as the ranking

by rate of air penetration.

Because of the instability of inks and the difficulties of reproducing their rheological properties, tests of ink penetration into paper are commonly carried out indirectly by using an oil. These tests commonly diverge from actual printing conditions in that the oil penetrates an uncompressed sheet of paper under capillary forces alone. It is conceivable, if not probable, that the rank of a group of papers as regards rate of oil penetration may be quite different when the penetration takes place into a compressed rather than an uncompressed sheet, regardless of whether the oil is driven by capillary forces alone or by high external pressures.

As was noted earlier, correlation between air and oil permeability may be expected if the wettability of the sheet by the oil is not a variable. Such a correlation has been suggested on several occasions, but has neither been substantiated nor disproved (see, for example, Shaw and Simmons (5)). In many respects, the study of air permeability is simpler and more convenient than that of oil permeability. A satisfactory settlement of the validity of the suspected correlation between air and oil permeability would constitute a definite gain in the general study of printability. The study of this correlation would ideally involve the examination of the air and oil permeability of papers in the compressed state. It seems very likely that the correlation between the two for uncompressed sheets would be the same as for compressed sheets.

HISTORICAL REVIEW

The Capillary Concept of the Fundamental Structure of Paper

In the past, a number of attempts have been made to determine the size of the pores in paper. It may seem pointless even to broach the question of the size of the pores in such a structure, inasmuch as the free spaces in the network of fibers that constitute a sheet of paper are extremely irregular and indefinite in shape and size. The fact remains, however, that much effort has been expended in attempting to assign some numerical value to characterize the size of the pores in paper and various other materials. And the effort seems justified, both by the practical usefulness of such a numerical characterization and by the behavior of the materials. Although there is probably no such thing in a sheet of paper as a long, cylindrical capillary tube, the sheet, nevertheless, behaves in certain respects as if its system of pores were made up of a large bundle of such capillary tubes in parallel, making it possible to talk about and write equations for a system of pores that behaves in certain respects like the system of pores in an actual sheet of paper.

"The porous nature of paper inescapably suggests that the movement of liquids into and through paper be considered in terms of capillary systems. The actual structure of paper is, of course, not accurately or even adequately described by any simple picture of a system of capillaries of varying radii. The pores in the sheet through

which liquids move are, in general, not even approximately tubular in nature but are more of the nature of the interstices of a compressed brush heap. However, in spite of the actual complexity of the pore system of a sheet of paper, it is recurrently hoped that the relationships describing simple capillary flow will be found applicable to the flow of liquids into and through paper.⁶ (10)

In general, the flow of liquids through a capillary, as through a pipe, may be either laminar or turbulent. If the directions of the stream lines through any cross section of the channel do not change with time, the flow is laminar; the flow is turbulent if the directions of the stream lines are not constant. In the very thorough investigation (10) to which reference was previously made, it was found that it appears to be quite safe to assume that the flow is laminar in any penetration of liquids into and through paper.

Mention of capillary flow most commonly suggests Poiseuille's law--i. e.,

$$U = (\pi R^4 P_0) / (8 \eta L),$$

$$\text{or, if } \phi = U/t,$$

$$\phi = (\pi R^4 P) / (8 \eta L),$$

in which U is the volume of liquid that flows out of a section of length L of a long straight capillary of constant internal radius R in time t when the pressure difference between the ends of the section is P ; η is the coefficient of viscosity of the liquid. The section of the capillary under consideration must be far enough from the ends of the capillary that no specific effects due to the ends of the tube

influence the flow through the section--i.e., steady laminar flow must occur.

The average speed of flow (v) is often of interest and is obtained by dividing the volume rate of flow ($\phi = U/t$) by the cross-sectional area of the capillary. It is

$$v = (\underline{R^2 P}) / (8 \eta L).$$

This equation may be used as the starting point for the derivation of equations which relate the filled length of the capillary to the elapsed time of flow for (a) flow of a liquid into a horizontal capillary due to capillary forces alone and (b) flow of a liquid into a vertical capillary due to capillary forces alone. It has been shown (10) that the flow of water becomes laminar within a very short distance of the end of a fine capillary, and for liquids of relatively low surface tension and high viscosity, such as castor oil, this distance is roughly a millionth of the value for water.

It is but a short step from the case of the single capillary to the system made up of a series and parallel combination of capillaries, which is of more practical interest. For this condition, the "equivalent capillary" is usually defined as the single capillary through which the volume rate of flow for a given pressure difference between the ends of the capillary is equal to the sum of the rates of flow through the individual capillaries.

A detailed discussion of the theory of wetting is not necessary at this point; however, one or two points of interest will be mentioned. In the particular case of capillary rise, "spreading"

involves no change in the area of the air-liquid interface and, hence, the free energy change is determined by the adhesion tension alone (adhesion tension is defined as the surface tension of the liquid times the cosine of the angle of contact between the liquid and solid surfaces). The condition that a liquid rise in the capillary is that the adhesion tension be greater than zero--i.e., that the contact angle be less than 90° . $\underline{T} \cos \theta$ is the effective force per unit length of solid-liquid interface causing the capillary rise; its maximum value is \underline{T} when $\cos \theta = 1$. \underline{T} is the surface tension of the liquid and θ is the contact angle.

It seems that, in most penetration processes, the major part of the flow takes place through the spaces or pores between the fibers, rather than through the channels within the fibers. Permeation of the fibers themselves is generally a slower process than the penetration between the fibers. The channels by which liquid passes through or along a sheet may consist of extremely irregularly shaped pores interconnected by many much smaller constrictions or orifices. Particularly in the case of the channels effective in penetration through a sheet, there can be little distinction between the lengths and diameters of the pores.

By straightforward application of capillary theory (10), it is possible to calculate the radius of the "equivalent capillary" for a system of capillaries. It is commonly found for paper that the values of equivalent radii so calculated are very small as compared with the size of pores as seen by microscopic observation. However, there

is no practical method of estimating the size or relative importance of the fine interconnections of the pores visible to the eye. The necessity for believing in these small radii can be evaded by considering the equivalent capillary lengths to be greater than the caliper of the sheet--in some cases many times greater, because of the tortuous nature of the actual channels.

Since the fibers are preponderantly oriented with their lengths in the plane of the sheet, the channels effective in the flow along the sheet direction probably differ in size, shape, distribution, and number from the channels effective in flow through the sheet. Consequently, effective capillary radii found for flow in one direction should be used to describe flow in the other direction only with due cognizance of such differences.

The fact that there are differences between the rate of flow of fluids through the sheet and the rate of flow along the sheet direction, as suggested above, has been borne out by the work of Sullivan and Hertel (11). They showed that, in expressing the permeability of a porous medium as a function having the form

" $K = \frac{g^3}{k S_0^2} \frac{A}{(1-g)^2}$ ", the value k must be given different values for different orientations of the exposed surface. In this equation

" K = permeability of the medium; g = porosity = free volume in medium divided by the total volume of the medium; S_0 = specific surface = sq. cm. for medium divided by cc. of solid portion; A = cross-sectional area of medium; k = proportionality constant." For glass fibers oriented parallel to the direction of flow of air, k was found

to be about 3.0, for those oriented perpendicular to the direction of flow of air, k was found to be about 6.0. The latter case is roughly analogous to the flow of fluids through a sheet of paper.

Peek and McLean (12) have developed a theoretical treatment of liquid penetration into fibrous materials as an extension of the theory developed by Washburn (13) for uniform capillaries. It was shown that the treatment for penetration into a porous medium is similar to that for a uniform capillary, save that consideration must be given to the fact that the variation in pore size causes the resistance to viscous flow of each channel to be similar to that of a number of capillaries in series. The final expression, therefore, involves quantities whose values depend on the distribution of pore sizes. Data were presented for the penetration of six organic fluids into strips of filter paper. It was shown that these data agree in character with the theory of the capillary nature of the paper.

The work of Carson (6, 7) has been monumental. He concludes that "The air passages through paper are very small, having cross sections of capillary dimensions. The length of these passages is an unknown quantity; it may be anything from the thickness of the paper to a comparatively lengthy and devious course through the sheet. The cross-sectional contours are irregular in shape and variable in size." All the evidence which he has been able to focus on the question has indicated capillary phenomena within the structure of the sheet. The criteria of pressure difference, temperature, and thickness (in the air permeability measurements on paper) showed a

remarkably close correspondence between experimental data and theoretical equations for the flow of air through long capillary tubes. This excellent agreement is a noteworthy circumstance and throws considerable light on the structure of paper. It is certain that the thickness of the paper does not represent the length of the path through the paper, as has been frequently assumed. Carson concludes that the length of the capillaries present in the sheet must be of the order of a thousand times as great as their diameter, or something like 100 times the thickness of the sheet.

Printability of Paper

Consideration of paper for printing is dependent upon properties and functions which, as far as paper testing is concerned, have until recently been almost entirely neglected. In this group of paper characteristics are finish (smoothness or roughness of the surface); ink receptivity; porosity or air permeability; surface strength or resistance to picking; opacity; formation; softness and compressibility; dusting and flaking; expansivity; moisture content; thickness; color and general appearance. The need of reliable methods for measuring some of these properties of paper has been strongly felt by both paper manufacturers and printers.

From time to time various methods have been devised for determining separately these characteristics of paper which are of importance from the standpoint of printability. However, no single instrument has been developed which will measure printing quality. In the final analysis the only true method of determining printability

is to actually subject the paper to printing--for example, in an experimental proofing press. The nearest means of reporting the printability as a whole is probably reached by means of such a proof press. Prior and Larocque are the principal exponents of the proof press in testing the printability of paper.

Larocque (14) has developed a method for printing paper with a hand-operated letter-press under controlled conditions of ink coverage and pressure. It was found that, in printing, the amount of ink transferred increases with the printing pressures. However, no measurements were made of the printing pressures.

Prior (15) used a hand-driven proofpress for experiments on the essential factors of printing--namely, type surface, ink film, printing surface, and pressure. The press gave uniform results which enabled the pressure and ink film to be measured and controlled, so that different papers could be compared for printing qualities. It was found that ink deposits on paper showed considerable irregularity when examined under a microscope, and that this irregularity controlled the appearance of the print. Various hypotheses were examined to account for the uninked areas, and such evidence as was available favored a lack of contact between the ink film and the paper due to their relative contours at the moment of printing, whereas surface tension effects and "wettability" appeared to be unimportant. The press was found to be very useful for predicting the relative behavior of different papers on a commercial basis, with regard to evenness and depth of printing, strike-through, and less directly, set-off.

The range of pressures that can be employed in printing was examined. If the pressure is too low, the print is patchy and uneven, and the upper limit is set by the embossing of the paper, the strain on the press and, in commercial practice, the possibility of wear and damage to the type. For an imitation art paper a pressure of 750 lb. per sq. in. was required to obtain a normal full impression, and heavy embossing set in at a pressure of 1000 lb. per sq. in. For a newsprint a pressure of 290 lb. per sq. in. gave only a slight impression, but at 800 to 900 lb. per sq. in. heavy embossing occurred. No data for intermediate pressures were given. The author of this work admitted that his figures may be in error by as much as 50 per cent.

Fairbrother (16) in his work on printing pressures found that a pressure of 600 lb. per sq. in. was required to "bottom" a cartridge paper, and at 800 lb. per sq. in., embossing set in. For glassine a pressure of 225 lb. per sq. in. gave a satisfactory print, and increasing the pressure up to 395 lb. per sq. in. gave no improvement.

According to Weymouth (16a), "--- the engravers proofpress under the proper handling becomes an instrument of paper testing whose accuracy has been checked many times directly with commercial presses. This procedure yields a result which can be visually interpreted and easily understood by all concerned including the printer and his customer. Simplicity is the keynote of a method which shows simply a printed result of an ink on Paper Samples A and B. All that the printer or his customer will later see can be predicted from such a

properly devised test."

The inks used by the printing industry must meet three basic requirements: quick drying, resistance to water, and absence of corrosive effects on the metal printing plates. The major constituents of these inks are oils, resins, driers, pigments, and dyes. A nonoxidizing mineral oil is used for newspaper ink, which "dries" entirely by absorption into the paper. A mixture of linseed and other oxidizable oils is used for printing fine papers, and lighter volatile solvents are used for rotogravure. The drying of this ink on the paper can take place entirely by absorption of the vehicle (as in the case of newspaper printing), by a combination of absorption and oxidation (in the printing of fine papers), or by evaporation of the solvent (in rotogravure printing). The appearance of the printed surface, as well as the speed and ease with which the process can be carried out will depend to a large extent upon the rate at which the ink dries--that is, upon the absorbency of the paper.

For instance, too rapid an absorption of the ink in newspaper printing will give rise to "strike-through"--in which the oil penetrates through the paper and seriously detracts from the appearance of the reverse side of the sheet. On the other hand, if the ink dries too slowly, "offset" and smudging of the sheet will follow during the subsequent folding and handling operations. The manner in which the printing process is affected by variations in the composition of the ink is more properly the dominion of the ink-maker.

It is thought that paper behaves as a rigid porous structure

into which the oil penetrates in accordance with the known laws of capillarity. The capillary pressure (P) which draws the oil into the paper will depend upon the surface tension of the oil, the mean effective capillary radius (R) of the paper and the angle of contact (A) at which the oil wets the paper. The relationship connecting them is:

$$P = (2\gamma \cos A)/R$$

This pressure was experimentally determined by Larocque (17) from measurements of the rate of penetration of oil under pressure, and was found to be of the order of one lb. per sq. in. for a bond and 1.6 lb. per sq. in. for a S. C. book paper. Larocque says: "These are quite small pressures compared to printing pressures which are of the order of 750 lb. per sq. in., but, since they act for a much longer time than the momentary impact of the printing pressure, they are generally considered to be the main forces that bring about the absorption of the printing oils into paper."

Penetrability of Paper for Nonswelling Liquids

Oil instead of printing ink has been used almost universally in investigations of the absorbency or penetrability of paper. The ways in which pure oils differ from actual printing inks as regards penetration into paper will be discussed briefly below, and the reasons will be pointed out why it has been necessary to use the pure vehicle or oil instead of the printing ink.

None of the theoretical relationships which have been previously discussed for the penetration of a capillary structure by

a true fluid can be assumed to hold for liquids (such as printing inks) which exhibit thixotropic properties and plastic flow. The rates and distances of penetration for such liquids should, in general, be less than those calculated from theoretical considerations, even for flow through ideal cylindrical capillaries.

Liquids or solutions containing a component which is highly sorbed by the fibers or furnish of paper may not behave according to the simple relationships, because of a continuous change in the adhesion tension of the liquid-furnish system as the highly sorbed component is progressively removed during penetration. It is, of course, quite possible that one or more of the components in a printing ink may be sorbed in this manner by the paper.

Liquids, such as printing inks, which contain dispersed material may show a complicated behavior because of the filtering-out of the dispersed material by pores near the surface of the sheet. The resistance to flow of the vehicle may thus be progressively increased as the effective cross sections of the surface pores gradually decrease, because of the accumulation of originally dispersed material.

Printing ink, due to its colloidal nature, cannot be exactly duplicated when it is prepared from time to time, and is furthermore subject to considerable change on aging. On the other hand, pure oils of suitable viscosity can be readily obtained. Since they are but little affected by aging, they give results which can be duplicated at any time. In addition, extremely small amounts of oil can be measured and manipulated with an ease and accuracy which cannot be attained with

printing ink.

To what extent one is justified in drawing conclusions as to the penetrability of paper for inks from data obtained for the penetrability of the ink vehicle or oil alone is a question which never has been, and perhaps never will be, definitely settled. To say that the data accumulated by the many investigators who have dealt with pure oils is valueless so far as determining the printability or penetrability of paper for inks is concerned would undoubtedly be untrue. On the other hand, it would probably be equally misleading to say that oil penetrability data represent directly the printability of the sheet. The views of Larocque (14, 17) represent the former of these two extremes, and those of Ant-Wuorinen and Backman (15) represent the latter. Larocque found that the amount of ink offset which can be made to take place immediately after printing is directly related to the resistance of the paper to penetration by oil. Hence, oil instead of oil and pigment was used by him in experimental printability determination work because of the greater convenience and accuracy. Ant-Wuorinen and Backman, on the other hand, concluded that "however interesting the question of the mutual behavior of paper and oil, the printability of paper cannot be judged beforehand on the basis of paper-oil tests, but this printability must be determined according to methods in which the ink itself acts on the paper to be investigated." Here, as in so many other instances, it is probably best to take a middle course and thus reach the conclusion that, although oil penetration data may not actually be representative of the true printability of the sheet, they are nevertheless of value in

predicting the ink penetrability of a sheet and are certainly of utmost importance from the standpoint of fundamental research into the printability problem.

It has been shown by Washburn (13) that the distance L which an oil of viscosity η and surface tension F will enter into a fine capillary tube of radius R in the time t is given by the relationship:

$$t = (\eta 2L^2) / F R \cos A).$$

From this equation it is seen that, apart from considerations of $\cos A$ (A is the contact angle), for any one sample of paper, the rate of penetration is proportional to the quotient F/η or surface tension/viscosity. Because most oils differ only slightly in their surface tension, viscosity should be the predominating factor in oil absorption. This has been shown by Larocque (17) actually to be the case.

Larocque has made measurements of the "oil-wettability" of various papers. Differences in the wettability of various papers are due to differences in the contact angle (A) which the oil makes with the material of the capillary walls. Such differences in wettability will not affect the air resistance of paper, but only the rate of oil penetration. Consequently, if two sheets are found to have the same air resistance but are different in oil resistance, as determined by rate of penetration, the sheet having the smaller apparent oil resistance will have the greater wettability. Larocque uses an "air-resistance/oil-resistance" ratio to express the relative wettability

of a paper.

A much more fundamental method is used by Foote (20), who measured the angle of contact formed between liquid surfaces and a fiber.

The spreading drop method (21) has also been used to measure the oil-wettability of a paper surface.

It has been shown (19) that, with rise in temperature, the change in oil-absorption time is directly proportional to the viscosity of the oil. Hence the following relationship can be set up:

$$t_o = (\underline{t}\eta_o)/\eta,$$

where \underline{t} is the observed absorption time and η is the viscosity of the oil at the experimental temperature T ; t_o is the corresponding absorption time and η_o is the viscosity of the oil at the standard temperature T_o . The importance of controlling and knowing the temperature of the sample during the absorption process is appreciated when it is noted that, for castor oil, the viscosity changes by approximately nine per cent per degree C. change in temperature.

Larocque (17) has observed that the addition of two per cent of rosin size had little effect on the air resistance of the sheet, indicating that the structure of the sheet was not appreciably changed. However, this amount of rosin size increased the wettability to oil by about 25 per cent.

Shaw and Simmons (5) tested 45 experimental book papers for smoothness, oil penetrability, and air permeability. The papers

containing fillers were penetrated by oil more rapidly than those without fillers. Fillers seem to increase the available absorptive surface of the absorptive constituents of paper. The air permeability was greater for the papers containing fillers than for those without fillers. By inclusion of fillers the tendency of the fibers to cement together is lessened. The number of internal air spaces and, consequently, the air permeability of the paper are therefore increased.

According to Larocque (17) the relative humidity of the atmosphere has a marked effect upon the oil resistance of paper. The sheet tends to open up and lose its structure as the relative humidity is increased, giving a consequent increase in its ink and oil-receptive properties. The effect is for the most part permanent, and is not restored by returning the paper to surroundings at a low relative humidity. Samples should therefore all be tested at the same relative humidity, and at no time previous to testing should they be subjected, even momentarily, to an atmosphere having a relative humidity in excess of that at which they are to be tested. This is not in agreement with the results of Carson (7), who found that the effect of relative humidity is in general unpredictable (see page 27).

The different methods which have been developed and applied to the measurement of the penetrability of paper for non-swelling liquids are so numerous that it is possible to mention only the more important ones here.

The time honored method of determining oil penetrability of a sheet of paper is to lay a small square of the paper on the surface

of the oil and measure the time for the oil to come through and give a uniform gray appearance to the sample. In a variation of this method, a drop of oil is allowed to fall upon the top surface of the sheet and the effect of penetration observed from the bottom side. The time required for the oil to penetrate the sheet and give a spot of uniformly gray appearance is observed.

Larocque (19, 17) has developed an oil absorption test by means of which "a thin and reproducible film of any suitable oil is placed on the surface of the sheet of paper that is to be tested. The oil film is then examined by reflected light and the time required for its complete disappearance into the sheet is considered to be a measure of the 'absorptiveness' or 'absorptivity' of the paper surface."

Many properties of paper are known to vary from point to point through a sheet. Since printing is primarily a surface process, it seems likely that a test of surface oil absorptiveness would show better correlation with printability than would a test for average absorbency through the whole sheet. This is just what the Larocque surface oil absorption test was designed to accomplish. The fact that this test actually fails to do this has been conclusively shown in a more recent investigation (22).

The Cobb sizing test (23) is based upon the principle of applying a test liquid such as water or oil, at room temperature, to the surface of the sheet within a confined area, for definite intervals of time, and subsequently determining the actual quantity of the liquid

absorbed through this surface by direct weighing.

Ant-Vuorinen and Backman (18) have made use of the Bausch and Lomb opacimeter to determine the "oil absorption ratio" of a sheet of paper. This oil absorption ratio represents the decrease in opacity of the paper due to the effect of the oil employed.

The Penescope and its modifications have been applied by several workers (24, 25, 26) to the study of the problem of oil penetrability. It is a very simple device for holding samples of paper so that they may be observed and tested for permeability to water, moisture, oils, etc. Albert (25) used the Westinghouse type of penetrometer, and has also compared (26) the Williams penetrometer and the Westinghouse cup, which differ mainly in the size of the orifice.

Bekk (27) has devised an apparatus for measuring the rate of penetration of liquids, fats, etc., through paper under controlled conditions of pressure. The apparatus eliminates the possibility of evaporation of the penetrating medium on the surface of the paper on which it emerges. This is stated to give a truer measurement of the rate of penetration than with existing methods, especially in dealing with impermeable papers. No definite relation between rate of penetration and the pressure driving the penetrating medium could be shown, using water and paraffin oil.

The first of the photoelectric instruments used for the measurement of oil penetration was the News Penetration Tester

described by Hammond (25). The operation of the instrument is based upon the change in reflectance of the surface of the sheet as the medium penetrates from the under side. A critical survey of this instrument has been given by The Institute of Paper Chemistry (4). Their experimental observations and the theory of the News Penetration Tester show that the instrumental readings are definitely dependent on the color and opacity of the paper. This fact constitutes a fundamental and serious objection to the use of this instrument.

The Institute of Paper Chemistry has developed a photoelectric instrument (1) for measuring the total diffuse light transmission of papers. The arrangement is such that an oil or grease film may be applied to the paper, and transmission may be measured as a function of time after application of the film. Rates of oil penetration may be computed, and illustrative figures are given. The design of the instrument is based on the finding that the exponential law of light absorption obtains when the paper is illuminated by light passing through a white, diffusing opal glass in immediate contact with the paper. Tests which justify the application of this law are given, and a formula for computing oil penetration speed is derived.

In a continuation of this work (2), an improvement was made in the method of calculating rates and distances penetrated from data obtained with The Institute of Paper Chemistry photoelectric penetration meter.

Vincent (3), using a modification of the instrument developed at The Institute of Paper Chemistry, has made photoelectric determina-

tions of the permeability of paper to fluids by observing the increasing light transmittance accompanying the displacement of air from the pores. Transmittance is plotted versus $\sqrt{(\text{time})(\text{surface tension})/(\text{viscosity})}$. The slope of this curve is called the "penetration slope." It is thus possible to express the rate of penetration as a single numerical index characteristic of the permeability of the paper. This "penetration slope" is independent of the thickness and color of the sample, as well as the viscosity and surface tension of the penetrating fluid. The method is especially suited to bonds, tissues, and highly absorbent papers. Color correction (the photoelectric cell is not equally responsive to all wavelengths of light) is accomplished by preparing a color filter from part of the paper to be tested.

Porosity or Penetrability of Paper for Air

Larocque (17) concludes that "there is good reason to believe that both oil and air penetrate through paper along identical capillary passages, subject to two minor conditions. (a) The oil must be non-polarized, as otherwise it might tend to become oriented or absorbed on the surface of the finer capillaries and give an inordinately high resistance to flow. (b) The sheet must be regarded as consisting partly of capillary passages, partly of voids that are closed off from the remainder of the system, and partly of air pockets which are recesses open at one end only. The capillary passages are equally accessible to air and to oil, the voids equally inaccessible to both, and the air pockets will be without effect upon the flow of air, but will allow the entry of oil to some extent with a resulting compression

of the entrapped air. The opinion generally held is that the capillary passages make up the bulk of the interior of the sheet, so that on the whole, both oil and air follow identical paths through the sheet."

Larocque (17) has attempted to relate the air porosity of paper as determined by the Gurley Densometer to the oil penetrability as found by the well-known oil flotation test. Other things being equal, it was found that the oil resistance of the paper is inversely proportional to the first power of the radius of the capillaries present in the sheet, whereas the resistance to air is inversely proportional to the second power. The reason for this is that for oil penetration, the driving force arises from the affinity of the oil for the paper, which involves the first power of the radius of the capillaries. For air flow, on the other hand, the driving force is supplied by an outside pressure.

If both the oil and air were forced through the paper by an externally applied pressure, and if we could assume that both the oil and the air behaved as true fluids (which is very nearly true), then we would expect both to obey Poiseuille's law, and thus there would be a direct correlation between such an oil penetration and air porosity.

Albert (26) found a linear relation between the Gurley air resistance and the quotient obtained by dividing the seconds for oil penetration by the paper thickness squared.

Shaw and Simmons (5) found that there appears to be a definite

relationship between air-permeability and oil-permeability data, the more open sheet having the more rapid oil penetration, but too few measurements were made on the same type of paper to warrant a numerical correlation.

It has been concluded by others (19) that the resistance to penetration by various nonswelling liquids which show zero contact angle with paper may possibly be judged by tests with a single liquid, or perhaps by measurement of the air porosity of the papers. Experimental evidence on this point is still not available.

There have been developed in the past a great number of instruments and methods of measuring the porosity or permeability of paper. Only the more important ones will be mentioned here.

Goldberg (29) has described the use of the Mariotte flask or constant pressure instrument and the inverted burette or varying pressure instrument for the measurement of porosity.

The familiar Gurley Densometer is a simple instrument for measuring the time required for 100 cc. of air to penetrate a given area of the paper. The pressure driving the air through the sample is not constant but decreases somewhat during the test.

The Lhonne and Argy porosimeter (30) measures directly the time required for 100 cc. of air to pass through 50 sq. cm. of the paper sample under a constant pressure between the two sides of the sheet corresponding to a head of 10, 20, or 50 mm. of water.

In the Emmanuelli porosity tester (31) air is forced through the sample under test and then through a short length of small capillary tubing. Manometers are used to measure the pressure differential across the sample and across the standard capillary. The volume rate of air flow is calculated from the pressure difference across the capillary of known dimensions.

Doughty, Seborg, and Baird (32) have built a porosity tester from an old Mullen tester. The principle of its operation is essentially the same as that of the Emmanuelli instrument mentioned above.

Hersberg (33) has described an instrument in which the volume of air sucked through a given area of paper by an aspirator at 10 cm. water pressure differential in a given time was measured by means of an ordinary gas meter.

The apparatus developed by Carson (6) seems to be the porosity instrument par excellence. The usual error due to edge leakage was eliminated by using an annular cell surrounding the inner test cell. A special pressure regulator was also designed to maintain a very steady pressure drop across the instrument. The air flow was measured by a capillary flow meter. With this instrument Carson (7) has also determined the effect of varying experimental conditions--such as pressure difference, time exposed to the air stream, area of test specimen, temperature, relative humidity, thickness of sheet, and absolute pressure. The results show that, with few exceptions, the flow of air is proportional to the pressure difference (for small pressure differences); proportional to the time of flow; proportional

to the effective area of the specimen; and inversely proportional to the thickness of the material. With the type of measuring instrument used, the permeability values do not depend upon the viscosity of the air. The effect of relative humidity is unpredictable. The air permeability of paper was found to increase somewhat with decreasing absolute pressure, an unexpected behavior which may be associated with an elastic expansion of the structure.

Determination of the Effective Pore Size in Paper

Most of the efforts that have been made to determine the size of pores in paper have been concerned with the behavior of fluids flowing within the structure of the sheet, and it is from this point of view that pore size has been tacitly defined by many workers. The values arrived at, of course, tell us little more than the average size, or range of sizes, in a system of simple pores which would behave, toward the flow of fluids, like the actual system of pores in the sheet. The sheet of paper does not necessarily contain any structural counterpart of the capillary system evaluated.

The microscope is a valuable means of studying the pore structure of paper. It does not, however, give the same type of information as do flow measurements. It does not readily reveal which spaces are the pores or continuous channels, or how the spaces at different levels are connected.

Edwards (34) made air-permeability tests on leather and found the average effective pore size to be about 0.5 to 1 micron.

He evaluated the fractional pore area by means of water-vapor-permeability data.

It has been shown (13) that, under certain conditions, the radius of the bore in a glass capillary is proportional to the square of the height to which a liquid that wets it will rise in a given time. Simmonds (35), after presenting data to show that certain papers behave approximately in conformity with this relation when strips are hung with the lower end in water, applied this equation to evaluating the size of the pores. He reported values for the average effective radius of pores in cartridge paperboard as about 0.008 to 0.045 micron; in blotting paper, about 0.1 to 0.3 micron; in sulfite pulp sheets, about 0.5 micron.

Peete (20) extended the experiments of Simmonds, using formamide, alcohol, and benzene, in addition to water. His measurements were made on sulfite bond, from a part of which the rosin sizing had been extracted so that readings could be obtained with water and formamide. His values for the average effective radius of the pores ranged from 0.006 to 0.35 micron, depending upon the liquid used in the experiments on capillary rise. He pointed out, however, that it may not be valid to assume that the contact angle is zero in all cases, and also that the equation used is probably not valid when the paper swells while the liquid is flowing through its structure.

Peck and McLean (12) measured the rate of rise of six organic liquids in strips of filter paper, and showed that the experimental data fitted their derived equation. By evaluating the constants of their equation they were able, on the assumption of a uniform

distribution of sizes, to calculate the range of pore sizes. They reported the values of 4 to 40 microns as the range of effective capillary radii of the filter paper with which they experimented.

Larocque (19) used a method based on capillary pressure. The value reported for the average effective pore radius in a super-calendered book paper was about 5 microns; in a bond paper, about 10 microns.

Carson (8) has outlined a new method, which takes advantage of the fact that the coefficient of slip of air in viscous flow through a paper is a function of pressure. From the Meyer equation, the average effective pore radius is evaluated in terms of the air permeability values at two pressures. It is only necessary to determine the air permeability at two different pressures of an identical area of the paper. The air permeability instrument previously developed by Carson (6) is used. Values given for the average effective pore radius range from 0.2 micron for double-coated book paper to 1.2 microns for bond paper.

Friess (36) has determined the pore size of porous media by filtering an isodisperse aerosol of titanium dioxide through the porous material.

Lechmann (9) has used the gas flow method of Adzumi to determine the average pore radius and number of pores per unit area of a pad of porous material. This method involves the measurement of the volume rate of flow of gas under unit pressure difference for a

number of average gas pressures.

It would be amiss to leave the subject of porosity determination without mentioning the great amount of work which has been done along parallel lines in the field of ceramics. Some of the workers in this field who might be mentioned are MacGee (37), Stull and Johnson (38), and Washburn and Duntz (39).

OBJECTIVES

The general objectives and plan of attack for this work have been mentioned in the introduction. The immediate and specific objectives will now be set forth. They are:

1. To study the air permeability of paper. Carson's instrument seems to be an excellent one for air permeability measurements. It has the advantage over others in the same field of being adaptable to measurements of pore size.

2. To study the oil permeability of paper under pressures comparable to ordinary printing pressures. Since no work has been done previously in the field of oil permeability of paper, it is necessary to design an instrument to fulfill this purpose. Ideally, it is desirable to be able to vary the pressure driving the oil through the paper independently of the total pressure compressing the sheet. Castor oil, or some similar oil, which closely approximates the vehicle used in printing inks will be used. All types of printing papers will be used (coated sheets, however, must be excluded). It seems desirable to use handsheets for the actual test specimens in order to obtain samples of as high a degree of uniformity as possible and in order to know accurately the past history of the specimens.

The further and more general objectives are aimed at the determination of the mechanism of the flow of printing ink into paper during the printing process. They are:

1. Study the flow of oil through paper under pressures comparable to ordinary printing pressures.

2. Secure proof of the validity or falsity of the suspected correlation between air and oil permeability of paper. A satisfactory settlement of this question would be a definite gain in the general study of printability.

3. The variables in sheet characteristics whose effects on air and oil permeability might be studied are: type of pulp, degree of beating, type and degree of sizing, type and amount of filler, etc.

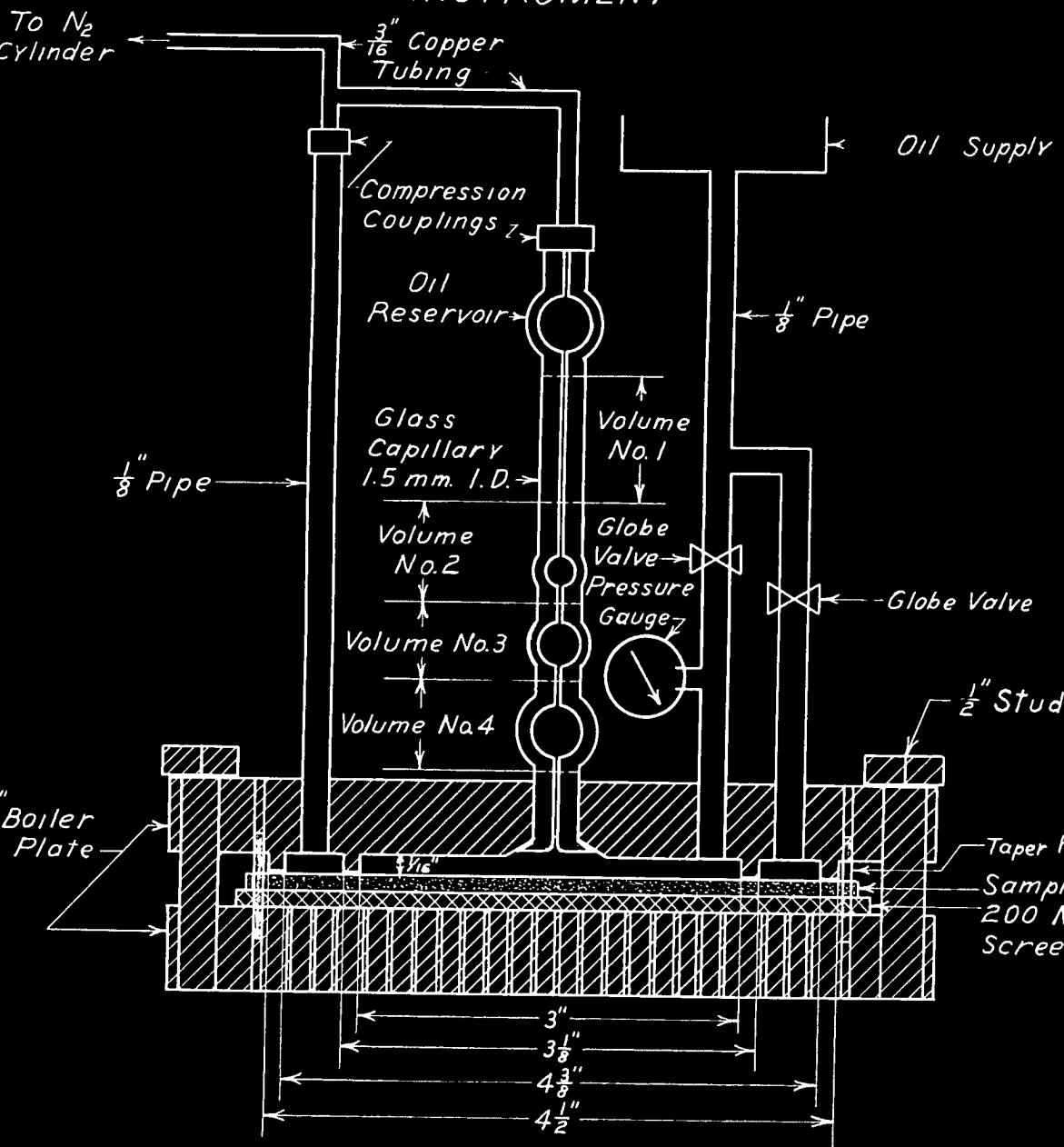
EXPERIMENTAL WORK

Description of the Oil Permeability Instrument

The preliminary oil permeability experiments of an exploratory nature revealed that papers such as newsprint, mimeo, bond, etc., had permeabilities of such magnitude that, using castor oil and a sample area about three inches in diameter, the amount of oil passing through in a minute was quite large--i.e., about 1 cc., even for driving pressures as low as 10 to 15 lbs. per sq. in. Accordingly, an instrument was designed and constructed which was capable of measuring permeabilities in this range. Figure 1 is a sectional view of the oil permeability instrument, and Figure 2 is a photograph of this instrument and also the air permeability instrument.

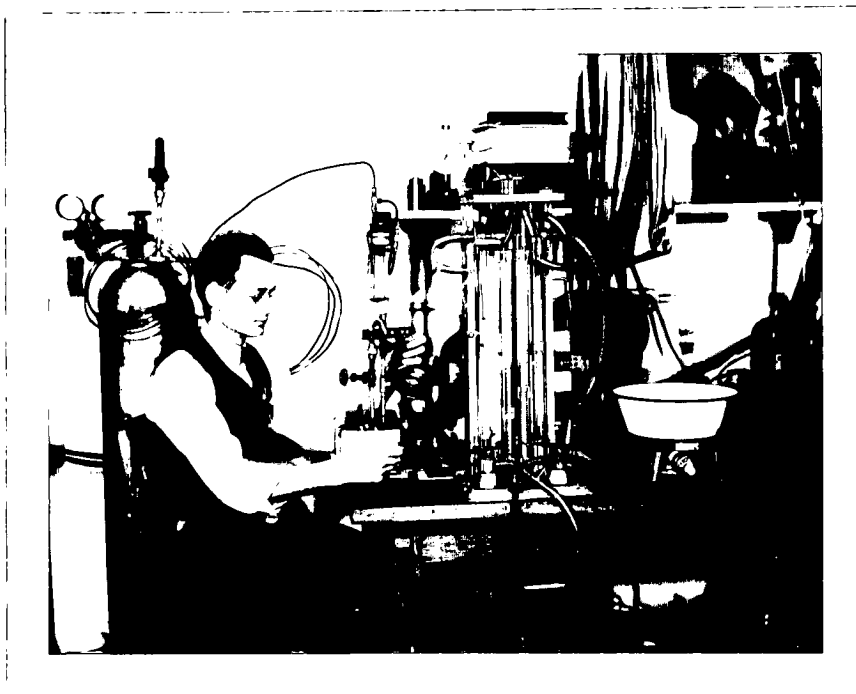
The specimen for oil permeability test is sandwiched between two pieces of $3/4$ -inch boiler plate which are held together by four $1/2$ -inch studs located at the corners of a square concentric with the circular test area. The lower plate is perforated by a rectangular array of 0.076-inch holes with $1/4$ -inch spacing between centers. A 200-mesh screen lies on the surface of this plate and serves to support the sample. Two taper pins are located as shown, their purpose being to hold the 200-mesh screen and the sample in place. These two taper pins have a further and more important objective: They are located in exactly the same spatial arrangement as regards the test area as are two similar taper pins in the air permeability instrument. The upper

FIGURE 1
THE OIL PERMEABILITY
INSTRUMENT



SECTIONAL VIEW

FIGURE 2



↑
THE
AUTHOR

↑
The Oil
Permeability
Instrument

↑ The Air Permeability
Instrument

half of the instrument has two concentric circular rims near its outer edge which ride directly on the sample. These rims are $1/16$ in. wide and extend $1/16$ in. below the lower surface of the plate. The inner diameter of the inner rim is 3 in. and the outer diameter of the outer rim is $4\frac{1}{2}$ in. These dimensions were chosen so as to be able to accommodate British handsheets after they had been cut square for calendering. The area of sample subjected to test is therefore 3 in. in diameter, and it is surrounded by a "guard ring" area having a width of $5/8$ in. Four holes have been drilled in the top plate. The one located directly above the center of the test area has tapering or recessed shoulders as shown. Into this hole there is fitted a glass capillary (approximately 1.5 mm. inside diameter) whose lower end is flanged so as to bear against the tapered shoulders of the hole in the top plate. A good fit was secured by grinding the glass capillary into place with carborundum powder. Shellac was used to seal the capillary to the plate. The capillary has four small bulbs blown in it. The upper one serves as a reservoir for the oil. The volumes indicated have the approximate values: No. 1 = 0.05 cc., No. 2 = 0.25 cc., No. 3 = 1.0 cc., No. 4 = 4.0 cc. Oil is admitted from the oil supply to both the guard ring and the test areas by the two openings shown near the right edge in Figure 1. These connections are all made by means of $1/8$ -in. standard steel pipe and fittings. The two valves shown are Jenkins $1/8$ -in. brass globe valves. The pressure gage is a 0 to 100-lb. "test gage" having a 3-in. face. The oil supply is contained in a 2-in. pipe cap and short nipple, the pipe cap being drilled and tapped to fit $1/8$ -in. pipe. The hole shown in the left side of the

sectional view of the top plate accommodates 1/8-in. pipe which, in turn, is connected to the nitrogen cylinder. In the line from the nitrogen cylinder there is first the usual diaphragm gage for controlling the pressure; next, a safety valve set for 170 lbs. per sq. in.; and, finally, a small valve opening to the atmosphere to serve as a bleeder. The line from the nitrogen cylinder is connected to the apparatus through 3/16-in. copper tubing (a large coil provides flexibility) and brass compression fittings. The connection to the upper end of the glass capillary is made with brass compression fittings using a compression ring cut from neoprene. A thermometer well (not shown in the sectional view) is so located in the top plate that a -5° to 50° C. thermometer graduated in tenths of a degree may extend some 3 or 4 inches laterally into the plate.

Briefly, the theory of the operation of the instrument is that, by applying the same pressure to the oil in the guard ring as is applied to the oil in the test area, there will be no pressure differential tending to drive the oil laterally into the sheet between the test area and guard ring area. In this way edge effects are eliminated and lateral flow of oil avoided.

Test for Leakage in the Oil Permeability Instrument

To test the oil permeability instrument for leaks it was set up with a piece of heavy sheet rubber clamped between the two halves of the instrument. Pressure was applied to the extent of 80 to 100 lb. per sq. in. while the oil level stood in the capillary at a

point between the oil reservoir and the next lower bulb. The absence of leaks of any sort was proved by the fact that it was impossible to detect any motion of the meniscus of the oil in the capillary. This test was repeated at frequent intervals throughout the work to be sure that the instrument was free of leaks.

"Blank" Determination on the Oil Permeability Instrument

With no sample in place and for a volume rate of flow of castor oil of approximately 0.09 cc. per sec., the pressure drop across the 200-mesh screen was found to be less than 0.1 lb. per sq. in. Since this rate of flow is considerably greater than any encountered in actual measurements, and since the pressure gage is not accurate to better than 0.1 lb. per sq. in., the "blank" correction was taken as zero.

Calibration of the Pressure Gage

The pressure gage used on the oil permeability instrument was calibrated at frequent intervals on a dead weight tester and the corrections applied to all gage readings. Since the gage can be read to the nearest 0.1 lb. per sq. in., this procedure ensures a corresponding accuracy.

Viscosity Determinations

In making permeability measurements it is necessary to know the viscosity of the oil in question over a considerable temperature range--e.g., 19 to 23° C.--to cover the normal temperature variations

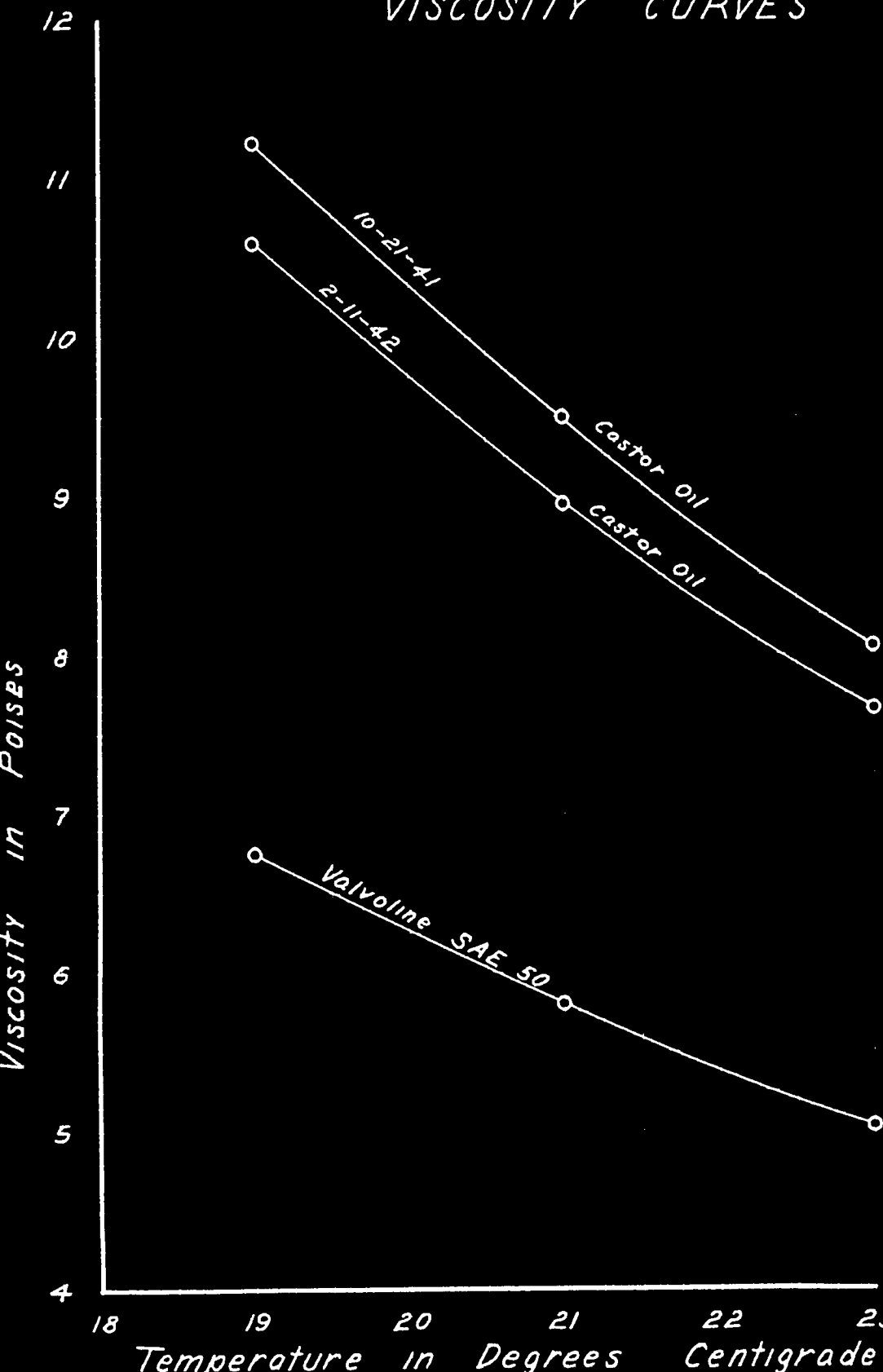
of the humidity room. The first oil permeability measurements were made with a castor oil whose viscosity was determined by means of an Ostwald viscometer. The standard of comparison was a castor oil whose viscosity was very accurately known. The viscosities of two separate batches were determined. Their viscosity variation with temperature is shown in Figure 3. Subsequent oil permeability measurements were made with a heavy mineral oil (Valvoline SAE 50). Its viscosity was determined with the Hoeppler viscometer, and the curve is also shown in Figure 3. It is necessary to know the density of the oil in question for the viscosity determination. Densities were determined with a Westphal balance. The density of the castor oil was 0.961 g. per cc. at 22° C., and that of the Valvoline SAE 50 was 0.884 g. per cc. at 21° C.

Calibration Procedure for the Oil Permeability Instrument

It is necessary that the volumes of the capillary bulbs of the oil permeability instrument be determined for different rates of efflux of the oil. The following technique was employed. With a sheet of rubber gasket material on top of the 200-mesh screen, the two halves of the instrument were bolted together. The valve in the line leading from the oil supply to the test area was opened. Oil was allowed to flow from the oil supply until it had filled the three lower bulbs in the capillary and half-filled the reservoir bulb. The valve in the oil supply line was then closed. The two halves of the instrument were then unbolted; the top half was removed, and set on two short pieces of 2 x 4 which served as supports. The lower side

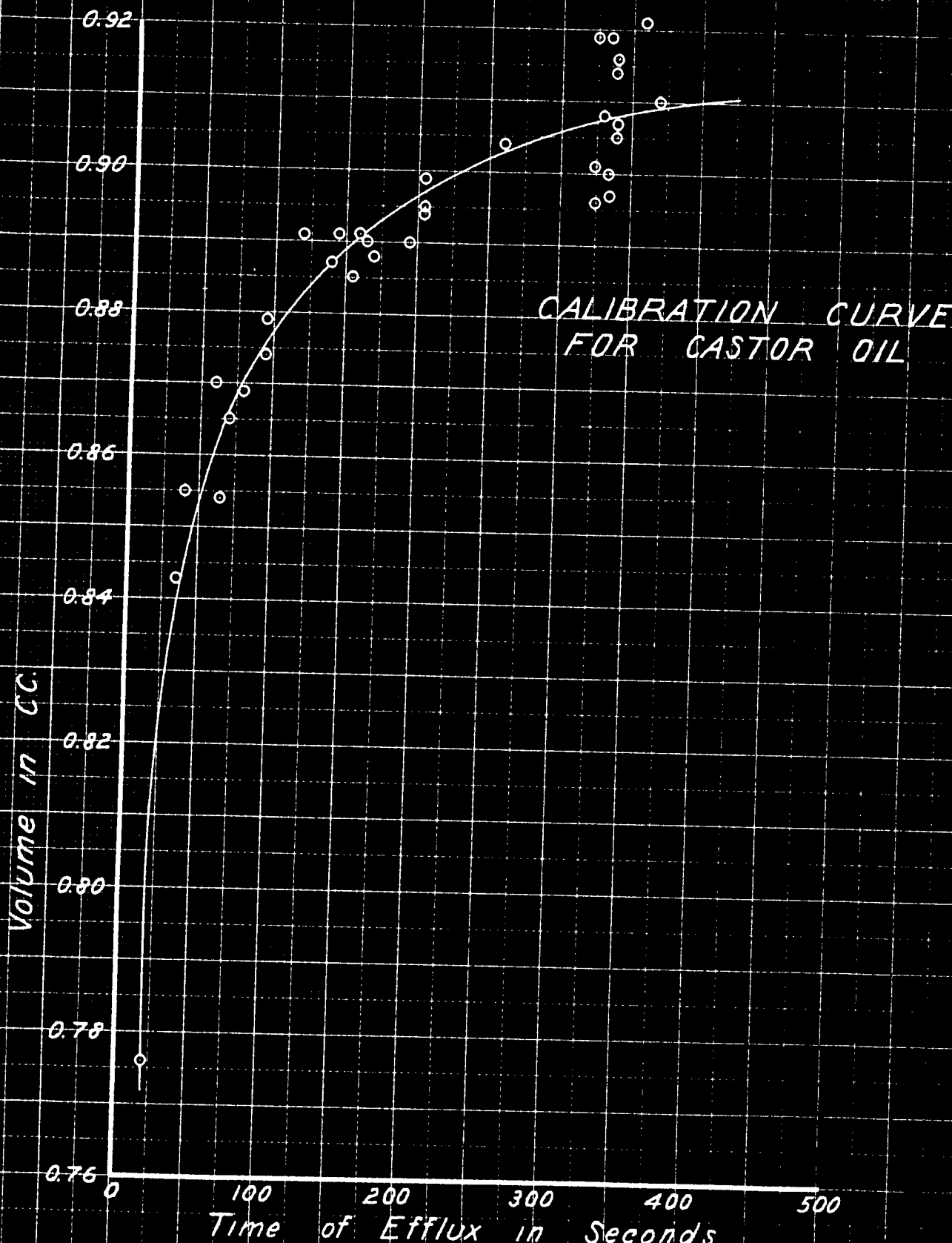
FIGURE 3

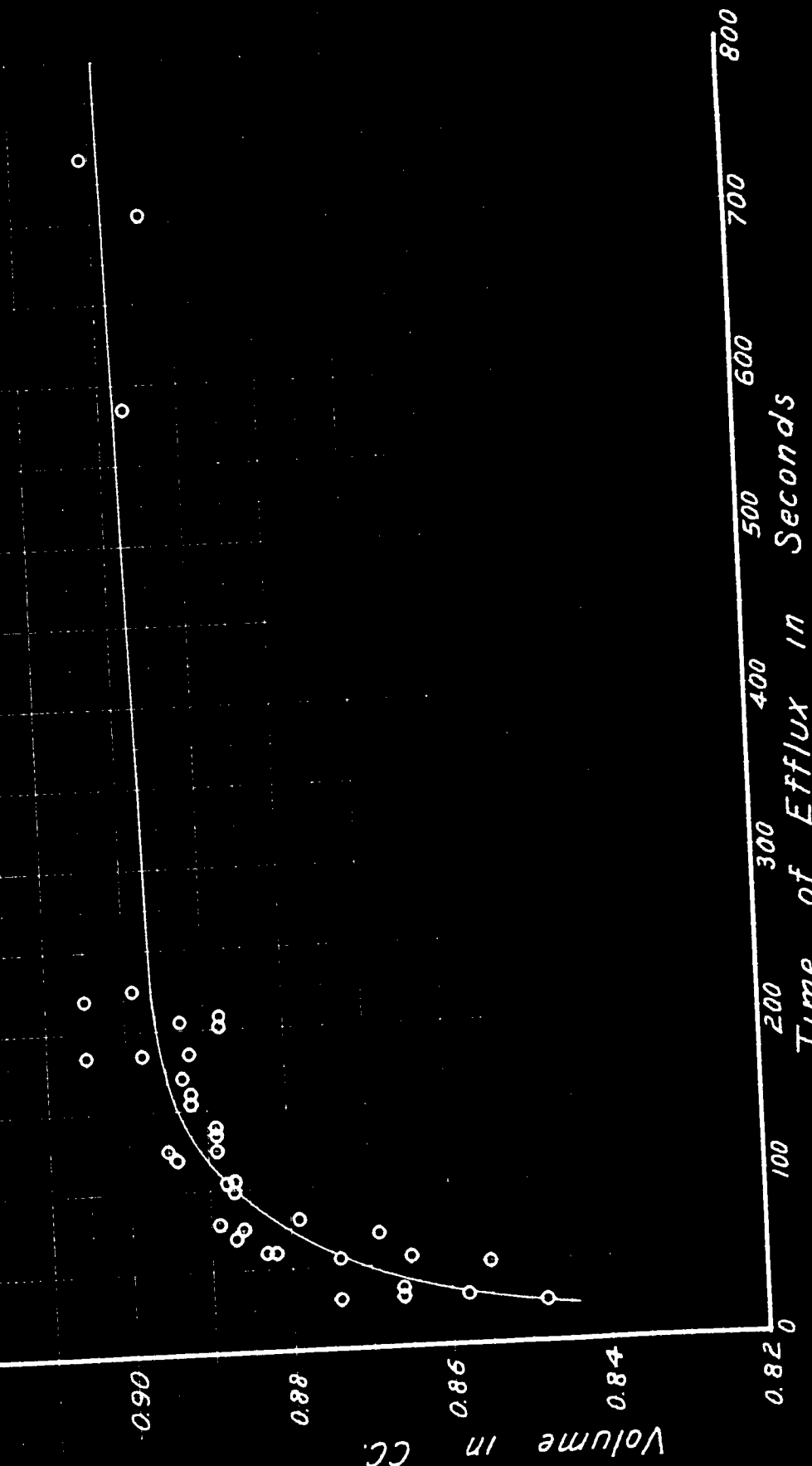
VISCOSITY CURVES



of the top plate was then carefully and quickly wiped free of all oil, paying particular attention to the bottom end or mouth of the capillary. Weighed cloths which had previously been allowed to come to moisture equilibrium with the atmosphere of the humidity room (all calibration and testing work was carried out in the constant humidity room at 70° F. and 65% relative humidity) were used to catch the oil as it flowed out of the capillary. The time of efflux was measured with a stop watch. Various rates of efflux were obtained by applying a slight pressure from the nitrogen cylinder. The volume of efflux was calculated from the increase in weight of the cloths and a knowledge of the density of the oil. In all cases a blank determination was made by carrying a weighed cloth through the entire procedure but without running any oil into it. The increase or decrease in weight of this cloth blank thus served as a correction to be applied to allow for small variations in weight of the cloths during the determination. In all cases this correction was small--i.e., of the order of a few milligrams on cloth samples weighing from 5 to 10 g. By taking great care to wipe the mouth of the capillary in the same way at all times, reasonably good precision was obtained in the calibrations. It may be seen from the calibration curves in Figures 4 and 5 that most of the points deviate from the smooth curve by no more than one per cent of the average volume. These calibration data are all for that bulb of the capillary marked "Volume No. 3" in Figure 1. It was later found that the other three bulbs added nothing to the accuracy or range of the instrument; consequently, they were not used for test work and their calibration data have not been shown.

FIGURE 4

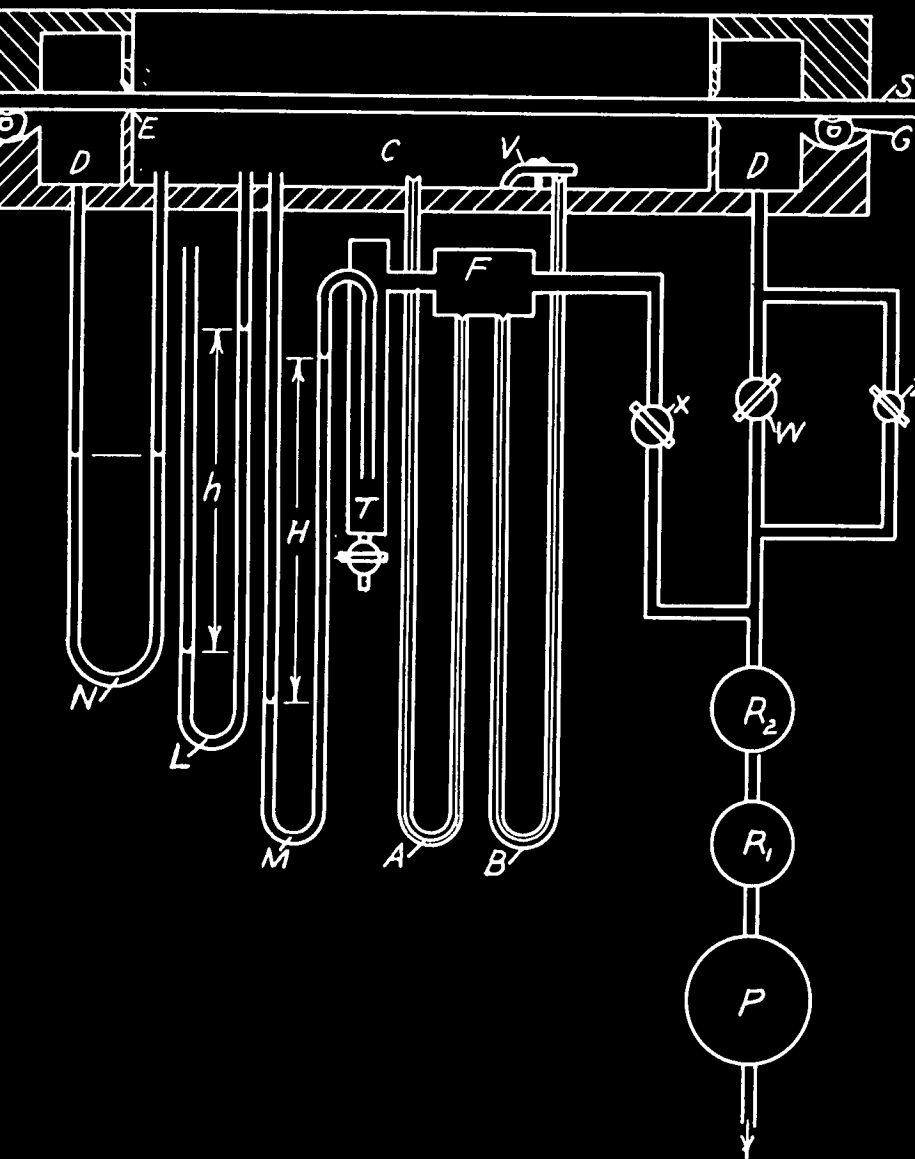




Description of the Air Permeability Instrument

A photograph of the air permeability instrument is shown in Figure 2, and a schematic drawing appears in Figure 6. This instrument is modeled rather closely after that of Carson. Although Carson (6, 7, 8) has given a very complete description of the instrument, its calibration and use, it is nevertheless deemed necessary from the standpoint of completeness to give a brief description of the instrument as constructed for the present work. Referring to Figure 6, the specimen (S) is clamped between two elements, each of which is composed of a central cavity or cell (C) and an annular cell (DD) separated by a circular wall terminating in a narrow edge (E), about $1/32$ in. wide at the line of contact with the specimen. A rubber ring (G) makes a seal between the annular cell (DD) and the atmosphere. Conditioned air at atmospheric pressure is accessible to the top side of the specimen in both the central and annular cells. By means of a mechanical vacuum pump (P), air is drawn simultaneously from C and DD, the relative flow being adjusted by valves W and Z (for coarse and fine adjustments) until the two menisci of manometer M are at the same level. Since the horizontal pressure difference across the boundary between the two cells is zero at any level, there can be no edge leakage into or out of cell C. Only the air which comes through that part of the specimen supported above the cell C is admitted to the measuring device, air reaching DD from the upper surface or through leakage at the edges being by-passed around the meter. The pressure drop through the specimen is measured with the manometer L.

FIGURE 6



SCHEMATIC DRAWING OF THE
AIR PERMEABILITY INSTRUMENT

This instrument is a comparison type of flow meter. As shown in Figure 6 the calibrated flow meter consists of the manometer M and 4 capillary tubes of different diameters, of which only 2 (A and B) are shown. The ends of these capillaries are sealed by small tab valves (V), of which only one is shown in the figure. By releasing the proper tab valve, any desired capillary may carry the air flow. If the rate of discharge through the capillary tube is known from calibration for all values of the pressure head (H), the value of H in any given test immediately shows the rate at which air is passing through the specimen under the pressure difference corresponding to H. One end of each capillary tube and one limb of each manometer are connected directly into the bottom of the permeability cell. The other end of each capillary tube is connected into a metal header (F), leading to the pressure regulators (R_2 and R_1) and thence to the air pump (P). A trap (T) is placed between the manometer (M) and this header to prevent the manometer liquid from inadvertently overflowing into the block and entering the capillary tubes.

The specimen area defined by the cell C is 45.60 sq. cm. (diameter = 3.000 in.). In order that appreciable sagging or stretching of paper over this large area may be prevented, the specimen is supported by a 1-inch ring (not illustrated) having a very thin contact edge. As a further preventive measure to eliminate stretching of the specimen, the pressure differential (h) across the sample is always kept below 12 cm. of kerosene.

The upper element of the instrument is caused to register

with the lower by means of two taper pins which extend through the outer rims of the top and bottom elements. These two taper pins have exactly the same spatial arrangement as regards the test area as do the taper pins of the oil permeability instrument. The two elements of the air permeability instrument can be clamped together with any pressure desired by means of a bar which fits on top of the upper element of the cell. This bar is fastened at both ends to studs which project upward from the wooden base in which the lower element is mounted. All connections into the lower element of the cell are made by means of 1/8-in. standard pipe nipples. The various capillaries and glass tubes are joined to the pipe nipples by means of rubber tubing. The header into which all four capillaries are connected was constructed of 1/8-in. standard pipe tees and nipples.

The manometer N requires no scale other than a horizontal reference mark. Manometers L and M were mounted in front of and clamped to meter sticks. That the meter sticks were sufficiently accurate for readings to 0.01 cm. was proved by checking them with an accurate steel rule. The meter sticks were mounted accurately perpendicular to the base of the instrument, which had been previously leveled. The meter sticks and manometers were clamped together at top and bottom by means of small clips made out of sheet aluminum. Manometer readings were accomplished with the aid of small aluminum verniers mounted so as to slide up and down on the meter sticks. Kerosene was chosen for the manometer liquid because water is likely to give false readings unless the manometer tubes are kept scrupulously clean. The density

of the kerosene was found to be 0.811 g. per cc. at 22° C. (Westphal balance). The fact that evaporation of kerosene from the manometers was negligible was established by the fact that, over a long period of time (3 weeks) during which the instrument was in constant use, the zero reading of the manometers did not vary enough to be detectable--i.e., less than 0.01 cm. All manometer readings were made by reading the meniscus of the upper leg and then the meniscus of the lower leg. When these two readings were subtracted and the zero correction applied, the true pressure difference in cm. of kerosene was obtained.

To test the apparatus for leakage, a heavy sheet of rubber is used in place of the specimen. A partial vacuum is created in the apparatus and the stopcock X is closed. If there is a leak anywhere (except in the tab-valves) that would affect the air permeability results, it will be indicated by a drop in the head h of manometer L. As a test for leakage in the tab-valves cell, C is left open at the top, all the capillaries are closed off with their tab-valves, a partial vacuum is created, and stopcock X is closed. Leakage will be indicated by a drop in head H of manometer M. The tests for leakage were applied at frequent intervals during the use of the instrument.

Capillary tubes of the required length and capacity were selected with the help of data published by Benton (40) so that the discharge rates at a pressure difference of 25 g. per sq. cm. would be well below the critical velocity, since the calibration is very uncertain in the neighborhood of the critical velocity. The capillaries have been referred to in the calibration work as C-1, C-2, C-3, and C-4.

C-1 has a diameter of 0.31 mm., C-2 of 0.64 mm., and C-3 of 1.21 mm. C-4 consists of a battery of four capillaries about 1.38 mm. in diameter and 15 in. long mounted in parallel. C-1, C-2, and C-3 are each about 35 in. long, and were bent in a U-shape to conserve space in the instrument.

The two pressure regulators (R_2 and R_1) were constructed similar to those used by Carson. A section from an old heavy-duty automobile inner tube was found to be satisfactory for the diaphragm of the pressure regulators.

After experience in the use of the instrument it was found that but one of the two pressure regulators (R_2 and R_1) is necessary, provided that the vacuum pump (P) creates a sufficiently good vacuum to give that one regulator a large pressure differential on which to operate. Incidentally, it was also found that the stopcock Z is superfluous.

Calibration of the Air Permeability Instrument

All calibration work was carried out in the humidity room at 70° F. and 65% relative humidity. Since Carson did most of his calibration with a wet gas meter, the author set out along the same path. But, of two meters available neither was found to be satisfactory for this purpose. Accordingly, the gas meters were discarded and a more direct method of calibration was devised.

Calibration of Capillary C-3: Air was sucked through the capillary, which was connected to the air space in a partially water-

filled bottle of 20-liter capacity, by syphoning water out of the bottle. The bottle, fitted with a four-hole rubber stopper, was placed on a shelf sufficiently high to give the syphon the desired head. A thermometer was placed in one of the holes. A second hole was connected to manometer L of the air permeability instrument which would normally indicate the pressure drop across the paper sample. This manometer, therefore, gave in this case the pressure difference between the atmosphere and the air space in the bottle. A third hole in the stopper was connected to the pressure regulator R, at the outlet normally connected to the vacuum pump. The fourth hole in the stopper carried a glass tube which extended nearly to the bottom of the aspirator bottle and formed one leg of the syphon. The other end of this glass tube was connected to rubber tubing which extended to a point some four or five feet below the level of the water in the bottle. This outlet end of the syphon was kept closed when not in use and the flow regulated when in use by a compressor clamp.

The calibration of the capillary was carried out in the following manner: The tab valve for C-3 and stopcock X were opened. The syphon clamp was adjusted so that water ran out at such a rate as to give the desired pressure drop across the capillary. By manually lowering the outlet end of the syphon as the water level in the bottle went down, it was possible to maintain a nearly constant pressure in the aspirator bottle. By manual manipulation of the pressure regulators it was possible to maintain a nearly constant pressure drop across the capillary. The run was begun, after equilibrium conditions had been reached, by thrusting a previously tared bucket under the syphon

outlet and at the same time starting the stop watch. The pressure in the bottle and the differential across the capillary were maintained constant as nearly as possible during the run. After the lapse of a suitable length of time the tared bucket was quickly withdrawn from beneath the syphon outlet, and simultaneously the stop watch was stopped. Then, and only then, the syphon was shut off with the compressor clamp. The time of flow, the weight and temperature of the water, the pressure differential across the capillary, the pressure and the temperature of the air in the aspirator bottle, and the room temperature were all recorded. From the temperature and weight of the water, the volume (under conditions of temperature and pressure prevailing in the aspirator bottle) of air drawn into the aspirator bottle from the atmosphere of the room can be calculated. Temperature and pressure corrections must be applied to give the true volume under conditions on the entrance side of the capillary. The capillary constant is $C = \phi / (\rho \underline{H} \underline{S})$, in which ϕ is the volume rate of flow under conditions prevailing on the entrance side of the capillary in cc. per sec. ρ is the density of the kerosene in the manometer (0.811 g. per cc.), \underline{H} the manometer reading in cm. and \underline{S} the area of the test cell (45.60 sq. cm.).

A pressure of one atmosphere is equivalent to approximately 1275 cm. kerosene. The plot of the data for C-3 is shown in Figure 7 and is marked "C-3(H₂O)".

Frequent checks of this setup for leaks were made as follows: The tab valves were all closed. The stopcock X was opened, and stopcocks W and Z were closed. Water was syphoned out of the bottle until

CALIBRATION CURVES FOR THE AIR PERMEABILITY INSTRUMENT

FIGURE 7

Capillary Coefficient $C = \frac{V}{P \Delta S}$

C-4

0.106

0.102

0.098

0.094

0.090

0.086

0.082

0.078

0.074

C-3

0.0078

0.0076

0.0074

0.0072

0.0070

0.0068

0.0066

C-2

0.000602

0.000598

0.000594

0.000590

0.000586

C-1

0.0000358

0.0000356

0.0000354

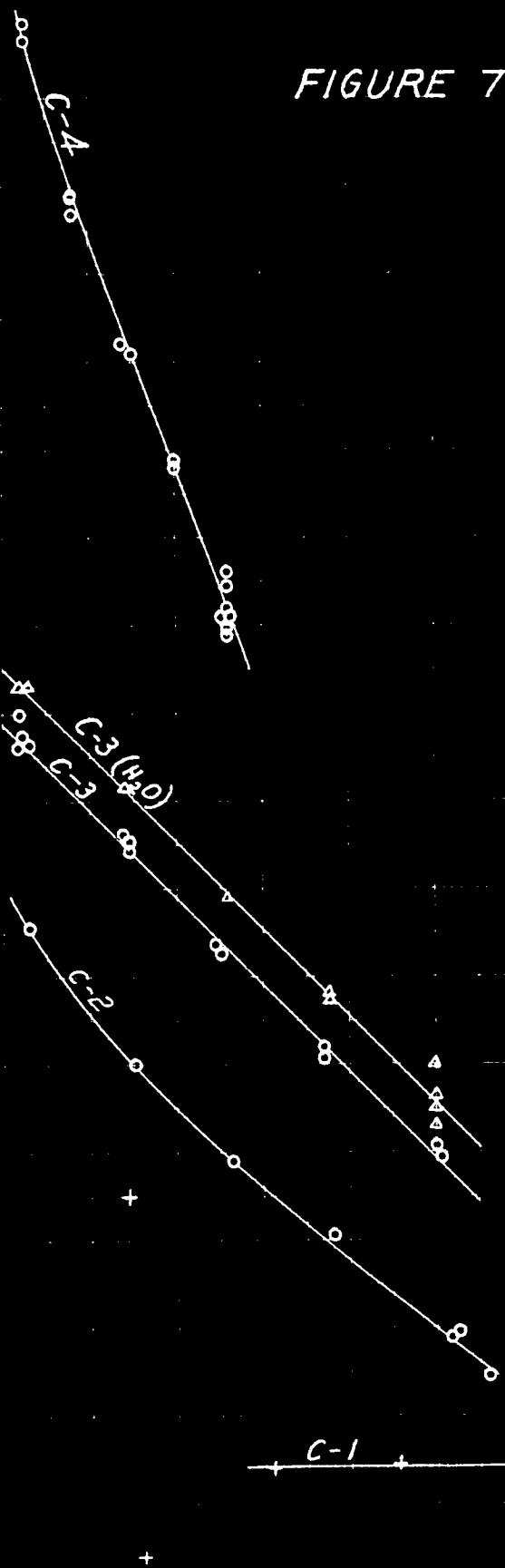
0

10

20

30

Cm. of Kerosene



a vacuum of some 25 cm. of kerosene was created. Stopcock X was then closed. Manometer M showed the pressure in the capillaries and the capillary header, and manometer L gave the pressure on the other side of stopcock X--i.e., in the pressure regulators and in the aspirator bottle. Any variation of these manometer readings during a period of several minutes indicated a leak. The pressure regulators were rendered air tight by generous application of castor oil. Leaks seldom occurred and were always traceable to the tap valves, which required frequent replacing --- a simple job.

After consideration it was decided that the accuracy of all the calibration data collected up to this point was open to doubt to the extent of about one per cent, due to the fact that no volume correction had been made for the change in saturation of the air as it passed from the atmosphere of the humidity room (65% R. H.) to the atmosphere of the aspirator bottle, which was nearly saturated. In order to accurately make such a saturation correction it would be necessary to have some sort of dew point apparatus in the aspirator bottle. It was decided that it would be simpler to eliminate the necessity for a correction by replacing the water in the aspirator bottle with some liquid of low vapor pressure, such as an oil. A crankcase flushing oil was secured for this purpose. The fact that the oil had a vapor pressure that was negligible compared to that of water was demonstrated by the observation that a 100-cc. beaker partially filled with the oil lost weight to the extent of only 0.008 g. in 11 hours, compared with a corresponding loss of 1.574 g. for water. The density of the oil at 21° C. was 0.9085 g. per cc. Using this oil,

capillary C-3 was recalibrated by the technique previously described. The data have been plotted in Figure 7 in the curve marked "C-3". It can be seen that the curves obtained with water and with oil in the aspirator bottle are both straight lines parallel to each other but separated by a distance equivalent to 10.5 parts in 1275. The explanation of this phenomenon is as follows: Assume that, when water was used in the aspirator bottle, the indrawn air changed from 65% R. H. in the room to 100% R. H. in the bottle. The vapor pressure of water is 1.865 cm. Hg at 21° C. The corresponding pressure in centimeters of kerosene is obtained by multiplying this value by the ratio of the density of mercury to the density of kerosene (13.6/0.811) and is 31.3 cm. of kerosene. The factor by which the volume of the air at 100% R. H. would have to be multiplied to obtain its volume at 65% R. H. is

$$\frac{1275 - \frac{[1.00 - 0.65] 31.3}{1275}}{1275} = \frac{1275 - 10.9}{1275}$$

In other words, the data obtained with water in the aspirator bottle are all theoretically too high by 10.9 parts in 1275. This theoretical value for the saturation correction is in very close agreement with the actual experimental difference as noted above of 10.5 parts in 1275.

At this point it is necessary to refer again to the work of Carson. In the calibration of his instrument Carson made use of the aspirator bottle principle for his smallest capillary, and employed a wet gas meter for the other three capillaries. Carson (6) mentions the corrections which must be made for changes in temperature and pressure. The fact that he does not mention the correction for change in volume due to change in degree of saturation of the gas as it passes through

the wet gas meter or into his aspirator bottle device in which the liquid was water leads inescapably to the conclusion that such a correction was not taken into account. That such a correction cannot safely be ignored has been shown above and is further emphasized by the fact that, in a private communication with the author, Carson himself admits the necessity of making such a correction.

Calibration of Capillary C-4: This battery of four capillaries in parallel was calibrated by the following technique: Since it was found to be impossible to obtain a sufficient head to cause the desired high rate of flow of the oil it was necessary to use the vacuum pump to aid the flow. The pump was connected to a T-tube, one arm of which was open to the atmosphere through a rubber tube, and the other arm connected to a two-hole stopper in a 5 gallon tin can. The tin can was mounted on the left pan of a torsion balance. Through the second hole in the stopper the can was connected by 1-in. glass and rubber tubing to the outlet end of the syphon from the 20-liter bottle containing the oil supply. To begin a run, an excess weight of about 2 kg. was placed on the right pan of the torsion balance. The vacuum pump was then started and the outlet to the atmosphere closed to such a degree as to give the desired rate of oil and air flow as measured by manometer M. The fine adjustment of this pressure differential was obtained by manual manipulation of the pressure regulators. At just the moment that the indicator of the torsion balance passed through zero the stop watch was started. Then an additional weight of 8140 gram was placed on the right pan. Throughout the run the pressure in the aspirator bottle was held nearly constant by manipulation of the

compressor clamp on the suction line open to the atmosphere. The pressure differential across the battery of capillaries was maintained constant by adjustment of the diaphragm valves, which, however, required little change once they were properly set. When the pointer of the torsion balance again passed through zero the stop watch was stepped and the run was over. The same variables were recorded and the calculation of the capillary constant (C) was made in the same manner as for C-3. The plot of the data is shown in Figure 7 as "C-4".

Calibration of Capillary C-2: After considerable experimentation the following method was found to be satisfactory. The aspirator bottle was set up in much the same manner as for the calibration of capillary C-3, except that it was connected directly to the air permeability instrument, thus by-passing the pressure regulators. The outlet end of the syphon tube was equipped with a glass tube drawn out to a tip so as to give approximately the right rate of oil flow out of the aspirator bottle without use of the compressor clamp on the line. The rate of flow was adjusted to any desired value by raising or lowering the outlet end of the syphon. Once the rate was adjusted to give approximately the desired pressure differential across the capillary, the outlet end of the syphon was fixed in position and not moved a bit during the remainder of the test. The pressure differential across the capillary drops slowly as the head producing flow of the oil gradually decreases. A determination is begun by thrusting a tared pail beneath the outlet end of the syphon and at the same time starting the stop watch. Every two minutes for a period of one hour the room

temperature, the temperature of the air within the bottle, and the top and bottom readings of the manometer are recorded. At the end of the run the pail is withdrawn from beneath the outlet of the syphon, and simultaneously the stop watch is stopped. It is not necessary to record the pressure within the aspirator bottle because, for such a small capillary, the pressure differential across the capillary corresponds almost exactly to the differential between the atmosphere of the room and that of the aspirator bottle. The temperatures are averaged to give an average room temperature and an average bottle temperature. The top and bottom readings of the manometer are averaged, subtracted, and the zero correction applied to give the true average pressure differential across the capillary. The weight of the oil divided by its density at room temperature gives its volume. Temperature and pressure corrections are made. A further correction must be applied due to the fact that there is some air in the aspirator bottle above the oil, and its volume changes during the run with changes in temperature. Therefore, all runs were begun with the oil level at a certain point, which left approximately 1700 cc. of air space above the oil. This volume correction is therefore

$$\frac{1700 (\text{temperature in bottle at beginning} - \text{temperature at end})}{293}$$

This correction is positive if the temperature in the bottle drops during the run, negative if it rises. The plot of the calibration data is shown in Figure 7 as "C-2".

Calibration of Capillary C-1: This capillary was calibrated by a method exactly similar to that used for C-2. The plot of the data

is shown in Figure 7 as "C-1".

A small error has been made throughout this calibration work by assuming atmospheric pressure to be 760 mm. Hg = 1275 cm. kerosene. A better figure for this locality would probably have been 740 mm. Hg = 1242 cm. kerosene. The error caused by this oversight has been calculated to be 0.6 part per 1000, which is not significant.

Check on the Continuity of Calibration

As confirmation of the continuity of the calibration from one capillary to the next, air permeability tests were made on samples in the three transition intervals of the four capillaries, an identical area being tested in each case with each of two successive capillaries. This procedure of making overlapping tests on an identical area of a given sample by means of consecutive capillaries is a simple and excellent means of periodically testing the capillaries for accidental fouling that might change the calibration. It dispenses with the necessity for recalibration except when positive evidence of the need is indicated. This test for continuity of calibration was carried out at the beginning of the work, near the middle, and at the end of the investigation. In all cases the two values thus determined for each sample agreed within 0.3 per cent.

Provision for Testing Exactly the Same Sample Area in the Oil and Air Permeability Instruments

As already stated, both instruments were drilled and equipped with two taper pins having exactly the same spatial relationship to

the test area. A paper punch was made by drilling a strip of steel so that the two holes were exactly the same distance apart as the taper pins in the two instruments. Each of these holes was equipped with a short piece of drill shank ground so as to have sharp shoulders. To punch a paper sample, it is placed on a strip of fiberboard, the punch is put on top of the paper, and then the two pieces of drill shank are struck a sharp blow with a hammer. The sample thus punched can now be placed on the taper pins of either instrument with complete certainty of always subjecting the same area to test in both instruments.

The Equation for μ_o

According to the Darcy equation $\frac{U}{t} = (\mu_o \frac{SP}{\eta L})$, where U is the volume in cc. of the liquid of viscosity η poises flowing in the time t sec. through the area S sq. cm. of the permeable medium having thickness L cm. and permeability μ_o sq. cm. due to the pressure differential P dynes/sq. cm.

$$S = 45.60 \text{ sq. cm.}$$

$$1 \text{ lb./sq.in.} = 68,944 \text{ dynes/sq. cm.}$$

$$\mu_o = \frac{(UL\eta)}{tSP}$$

$$\mu_o = \frac{\text{cc.}}{\text{sec.}} \times \frac{\text{caliper (in.)}}{\text{lb./sq.in.}} \times \text{poises} \times \frac{1}{45.60} \times \frac{2.54}{68,944}$$

$$\mu_o = \frac{\text{cc.}}{\text{sec.}} \times \frac{\text{caliper (in.)}}{\text{lb./sq.in.}} \times \text{poises} \times 3.08 \times 10^{-7}$$

This is the equation used for the calculation of the oil permeability,

μ_o in sq. cm.

The Equation for μ_a

The capillary constant is $\underline{C} = \phi / (\rho H S)$.

$$\phi = \frac{U}{t} = \frac{C_{OHS}}{1242} \left[(1242 - \frac{h}{2}) / 1242 \right]$$

The factor $(1242 - \frac{h}{2}) / 1242$ has been inserted to correct the volume rate of flow from conditions prevailing on the entrance side of the capillary to the algebraic mean pressure in the flow channel (pressure at a point half way through the sample under test). For an explanation of this procedure see page 78 of Maskat (41). The term h is the pressure differential across the sample in cm. of kerosene, 1242 is atmospheric pressure in cm. of kerosene, and the other terms have been defined previously.

$$\mu_A = (UL\eta) / (tSP)$$

L = sample thickness in cm. = caliper (in.) $\times 2.54$

P = pressure in dynes/sq. cm. = $980\rho h$

$$\mu_A = \frac{U}{t} \times \frac{1}{S} \times \frac{L}{980\rho h} \times \eta$$

$$\mu_A = \frac{h}{h} \times \frac{1242 - h/2}{1242} \times \frac{C}{980} \times \text{caliper (in.)} \times 2.54 \times \eta$$

This is the equation used for the calculation of the air permeability,

μ_A , in sq. cm.

It is obvious that the equations for μ_A and μ_0 have identically the same form initially, being simply a statement of the Darcy equation. However, on developing the two equations as shown above so that experimental data might be inserted directly into them, it is seen that the final forms differ considerably.

Applicability of the Darcy Equation

The Darcy equation is applicable only when conditions of viscous flow obtain within the permeable medium in question. According

to Muskat (41), a necessary and sufficient condition for the occurrence of viscous flow is that μ computed by the Darcy equation be constant for several different rates of flow. In the oil permeability measurements different rates of flow are secured by varying the pressure driving the oil through the sheet. Since the caliper of the sample varies directly with the pressure, measurements of oil permeability at different pressures would be expected to exhibit a corresponding variation. The data for μ_0 in Tables V and XIII are in agreement with this line of reasoning. The fact that the oil permeability values decrease gradually in the same way as does caliper and the additional fact that no sharp change in oil permeability occurred with increasing driving pressure are taken as sufficient reason for assuming laminar flow of oil through the sample. Further data have been secured, as shown in Table XIII, which prove that the air permeability is constant for a wide range of values of h (the pressure differential across the sample), and consequently the Darcy equation is applicable. Since these data have been secured on samples having a very high permeability, it is safe to assume that conditions of viscous flow also obtain for the less permeable samples. Carson (7) in his investigation of the effect of pressure difference on the rate of flow of air through a wide variety of types of paper found similar results.

Technique of Air and Oil Permeability Measurements

For a sample of unknown permeability it is first necessary to make rough air permeability measurements to establish the permeability range. Then it is possible to decide whether the oil permeability

measurements can be made on a single sheet, or whether it is necessary to use a sample consisting of several sheets in series in order to secure a sufficient pressure drop in the oil permeability instrument. If a composite sample of several sheets in series is to be used, it is necessary to first seal the edges with molten wax, as recommended by Carson, for a short distance into the guard ring area. This procedure has been found to be effective in both the air and oil permeability measurements for preventing edge leakage or lateral flow between the test and guard ring areas in those samples in which more than one sheet thickness was used.

The sample is punched with the specially prepared punch as mentioned previously so that it can be placed in both the oil and air permeability instruments in such a manner that exactly the same area will be subjected to test in the two instruments. This is necessary because variations in the air permeability as great as 50% have been observed (6) when different areas of the same sheet of paper were subjected to test.

The caliper measurements are next made with the Federal Compressibility Gauge (42). With this instrument it is possible to measure caliper to the nearest 0.00002 in. at the following pressures: 5.7, 9.0, 19, 40, 60, 80, and 100 lb. sq. in. In calculating oil and air permeabilities it is necessary to use that value of the caliper obtained at the same pressure as the pressure used in the oil permeability measurement. In those cases where deviation has been made from this procedure, notation has been made to that effect in the tabulated

data. For those samples consisting of more than 5 sheets in series four measurements of caliper, distributed in a representative manner over the sample area, were averaged to obtain the true caliper. For samples consisting of from 2 to 5 sheets in series the average was taken of eight separate caliper measurements. For single sheets the average was taken of 17 separate caliper measurements distributed uniformly over the sample area.

After caliper measurements have been made, the sample is ready for air permeability measurements. That capillary is used which will give for the sample in question a pressure differential (h) across the sample of from 5 to 12 cm. of kerosene and a pressure differential (H) across the capillary itself of from 5 to 30 cm. of kerosene. The reading of manometer H (Figure 1) is adjusted to zero before readings of h and H are made. From the values of h and H , the air permeability (μ_A) in fundamental C.G.S. units, sq. cm. can be calculated with the equation given previously. In the calculation of air permeability values the viscosity of air at 65% relative humidity and 70° F. has been taken as 181.3×10^{-6} poises. This value is independent of changes in absolute pressure and does not vary by more than 0.3% for temperature variations of $\pm 1^\circ$ C. The permeability range of the instrument is at least 1 to 300,000. Within this range its accuracy, as stated by Carson (6), is well within 1%, and its precision within 0.2%. (At this point it is important to note that the word "accuracy" implies a rigorous calibration technique and the absolute avoidance of all systematic errors. Carson errs when he claims an accuracy of 1% and yet allows a systematic error greater than this amount to enter his

calibration procedure, due to neglect of the saturation correction.) It may be mentioned in passing that throughout the work it has never been possible to observe any change in the air permeability of a sample even after large quantities of air have been sucked through it, provided, of course, that the sample had been seasoned for a sufficient length of time to come to complete moisture equilibrium with the atmosphere of the humidity room.

After the air permeability measurement has been completed, the sample is removed from the instrument. The oil permeability instrument is then unbolted and its two halves separated from each other. The 200-mesh screen is removed from the surface of the bottom part of the instrument and the bottom part blotted dry of oil. The 200-mesh screen is also blotted dry of oil and replaced in the instrument. This procedure is necessary to prevent the possibility of any oil penetrating the sample from the bottom side. The sample is next placed on top of the 200-mesh screen with the same side uppermost as in the air permeability measurement. The top half of the instrument is put in place and quickly bolted down. Oil is admitted from the oil supply and measurements begun at once. If the sample is a single sheet it will be completely permeated by oil even before the first measurement can be completed. If the sample consists of several sheets in series it is necessary to flush the sample several times at a high rate of oil flow to aid in removing the air. In making oil permeability measurements, the amount of oil forced through the sheet is roughly equivalent from one measurement to the next. Between measurements it is necessary to release the pressure from the nitrogen cylinder and replenish the

oil in the capillary bulb from the oil supply. In flushing a sample, a volume of oil is forced through which is roughly equivalent to 2-1/2 times the amount in an oil permeability measurement. In making an oil permeability measurement the time in seconds is recorded for the amount of oil represented by Volume No. 3 to flow through the sample. The volume in cc. is read from the calibration curve in Figure 4 or 5. This volume is probably accurate to within 1% or 2%, since most of the calibration data lie within 1% or 2% of the calibration curves. The temperature of the upper half of the instrument, and of the oil within it, is read to the nearest 0.02° C. on a -5° to 50° C. thermometer graduated in tenths of a degree C. Since the same thermometer was used in the permeability measurements as was used in determining the viscosity-temperature curves of the oils, the relative temperature measurements are accurate to about 0.02° C. The viscosity of the oil can be read from the curves in Figure 3 to within about 0.2%. During a permeability determination the pressure is recorded to the nearest 0.1 lb./sq. in. The gage reading is probably accurate to the nearest 0.2 lb./sq. in. after the gage corrections are applied. In the column "lb./sq. in." recorded in the tabulated data the gage corrections have already been applied, so that the readings recorded are true pressures. From a consideration of these factors, it may be stated that the oil permeability measurements are probably accurate to within 3%, the limiting factor being the accuracy of the pressure gage and depending to some extent on the pressure at which the instrument is being operated. (If pressures can be determined to the nearest 0.2 lb./sq. in.,

then the pressure can be determined with an accuracy of 0.2% at a pressure of 100 lb./sq. in. but can be determined with an accuracy of only 4% at a pressure of 5 lb./sq. in.). The range of the oil permeability instrument is about 1 to 4000. It is governed by three factors: the range of the pressure gage, which is from 5 to 100 lb./sq. in., the range of sample thickness, which is from 1 to 20 sheets in series; the range of the time of efflux, which is from 40 sec. to 400 sec. By using oils of higher or lower viscosities and recalibrating the instrument, this range may be considerably extended. Calibration involves, of course, the determination of the density and viscosity of the oil at several temperatures and the determination of the volume of efflux of the capillary bulb of the instrument over a wide range of rates of efflux. However, the instrument may be used with oils of unknown viscosities and without recalibration if it is desired to determine only the relative change in the oil permeability as oil is forced through the sample. This fact has been made use of in Table X and in Table XVIII.

In the operation of both the air and oil permeability instruments sufficient clamping pressure has always been used to cause the clamping ring which separates the guard ring and test areas to emboss the sheet heavily. In the oil permeability measurements variations in the clamping pressure were found to have no effect on the results, provided the sample was clamped firmly enough to emboss it. Carson (6) has found that heavy clamping pressure is not necessary in the air permeability measurements; however, it is best to be on the safe side and clamp the sample with moderate firmness.

Preparation of Handsheets

The handsheets used in this work were all prepared from a west coast bleached sulfite pulp, except those of Beater Run No. 3 which were prepared from a hardwood bleached kraft (equivalent to bleached soda pulp). A new wire for the British sheet mold was set aside for this work alone. The pulp was beaten in a laboratory beater in accordance with TAPPI Standard T 200 m-40, except that 3500 g. were placed on the bed plate for all the pulps. Samples were withdrawn at the intervals shown in the data for Schopper-Riegler freeness tests and for making handsheets. The handsheets were formed according to TAPPI Standard T 205 m-40 with the following exceptions. In couching the sheet, a Whatman's No. 1, 18.5-cm. filter paper was placed next to the sheet. On top of this were placed two dry blotters and couching was otherwise carried out as usual. After the sheet was couched a moist Whatman's No. 1, 15.0-cm. filter paper was placed on the exposed side of the sheet. It is essential to previously moisten this filter paper, otherwise the dry filter paper tends to wrinkle as it comes in contact with the wet surface of the sheet, and the wrinkles thus formed cause imperfections in the surface of the sheet. The whole object here is to obtain a sheet of uniformly smooth surface on both sides. The sheet between the two filter papers is placed between two dry blotters. As each additional sheet is formed and placed on top of the stack of wet sheets a dry blotter is used to separate it from the previous sheet. Thus, a stack is built up in the following order: dry blotter, 15.0-cm. filter paper, wet sheet, 18.5-cm. filter paper, dry blotter, etc. Great care is necessary to center exactly all the

handsheets, filter papers, blotters, etc. A dry blotter is placed on top of the stack of wet sheets and the stack placed in the press. Pressure is brought up to 50 lb./sq. in. in one-half minute and maintained there for 5 minutes. No second pressing is made. The sheets are placed in the drying rings without removing either of the filter papers and in the following order: drying ring, 18.5-cm. filter paper, handsheet, 15.0-cm. filter paper, polished drying disk, 15.0-cm. filter paper, handsheet, 18.5-cm. filter paper, drying ring, etc. It is to be noticed that the handsheet is always separated from the polished metal drying disk by a filter paper. This prevents the glazed effect which is obtained on one side of sheets made by the usual procedure. The handsheets were dried in the humidity room (the handsheets of Sizing Run No. 3 are an exception to this rule, since they were dried on a steam drier). After being removed from the drying rings, the sheets were further seasoned for several days before testing.

In regard to the physical data reported in Tables XIX, XX, XXI, XXII, XXIII, XXIV, and XXV, it should be stated that all tests were made in accordance with the methods of The Institute of Paper Chemistry. All data are on the air-dry basis. The data given for the Fuess oil penetration were obtained for penetration from the wire side towards the felt side. Similarly for The Institute of Paper Chemistry Oil Penetration Tester, the penetration took place from the wire side towards the felt side. Castor oil was used in the I. P. C. instrument, and the data reported are velocity of penetration of castor oil in mils per sec. at a depth of 2.00 mils.

TABLE I

MEASUREMENTS ON A COMMERCIAL MIMCO PAPER WITH CASTOR OIL

- (a) Sample: 14 thicknesses of mimeo
 Caliper = 0.0585 in. at 19 lb. per sq. in.
 C-3 --- $\underline{H} = 9.74$ $\underline{h} = 10.12$ $\mu_A = 1.935 \times 10^{-10}$ sq. cm.

<u>sec.</u>	<u>cc.</u>	<u>lb./sq.in.</u>	<u>η, poises</u>	<u>$\mu_0 \times 10^{10}$ sq. cm.</u>
144.2	0.887	19.0	9.05	1.384
144.6	0.887	18.9	9.17	1.405
155.8	0.889	18.3	9.57	1.410

Prior to the first measurement the sample was flushed with oil three times at 90 lb. to aid in displacing the air.

$$\frac{\mu_A}{\mu_0} = \frac{1.935}{1.405} = 1.38$$

- (b) Sample: 20 thicknesses of mimeo
 Caliper = 0.0836 in. at 19 lb. per sq. in.
 C-3 --- $\underline{H} = 8.39$ $\underline{h} = 12.79$ $\mu_A = 1.89 \times 10^{-10}$ sq. cm.

<u>sec.</u>	<u>cc.</u>	<u>lb./sq.in</u>	<u>η, poises</u>	<u>$\mu_0 \times 10^{10}$ sq. cm.</u>
225.5	0.899	19.9	9.85	1.332
222.9	0.899	20.0	9.66	1.314
222.8	0.898	19.5	9.50	1.323
220.8	0.898	19.7	9.37	1.310

Prior to the first measurement the sample was flushed with oil several times at 90 lb. to aid in displacing the air.

$$\frac{\mu_A}{\mu_0} = \frac{1.89}{1.32} = 1.43$$

TABLE II

MEASUREMENTS ON "WHITE VALLEY BOND" WITH CASTOR OIL

Sample: 1 sheet "White Valley Bond"

- (a) Caliper = 0.00412 in. at 9.0 lb. per sq. in.
 C-3 --- $\underline{H} = 32.20$ $\underline{h} = 6.30$ $\mu_A = 6.84 \times 10^{-11}$ sq. cm.

The air was displaced by oil previous to placing the sample in the oil permeability instrument by coating the top side of the sheet with oil and allowing it to penetrate the sheet under capillary forces alone.

sec.	cc.	lb./sq.in.	η , poises	$\mu_0 \times 10^{-11}$ sq. cm.
58.3	0.861	10.1	9.37	4.56
77.7	0.871	7.9	9.37	4.43
71.6	0.867	8.8	9.35	4.29
66.2	0.865	9.9	9.33	4.10

$$\frac{\mu_A}{\mu_0} = \frac{6.84}{4.56} = 1.50$$

- (b) Caliper = 0.00418 in. at 9.0 lb. per sq. in.
 C-3 --- $\underline{H} = 32.20$ $\underline{h} = 8.24$ $\mu_A = 5.14 \times 10^{-11}$ sq. cm.

The air was displaced by oil previous to placing the sample in the oil permeability instrument by coating the top side of the sheet with oil and allowing it to penetrate under capillary forces alone.

sec.	cc.	lb./sq.in.	η , poises	$\mu_0 \times 10^{-11}$ sq. cm.
103.0	0.878	8.2	9.50	3.32
115.2	0.881	9.2	9.50	3.56
83.6	0.873	9.5	9.50	3.71
94.1	0.876	8.4	9.47	3.54
95.0	0.876	8.7	9.45	3.38
98.6	0.877	8.15	9.43	3.47
81.4	0.872	10.0	9.32	3.37
87.0	0.874	9.75	9.37	3.26
102.5	0.878	8.0	9.37	3.38
93.5	0.876	9.0	9.37	3.29
92.0	0.875	9.5	9.37	3.17
98.7	0.877	8.9	9.37	3.16
90.5	0.875	10.0	9.37	3.06

$$\frac{\mu_A}{\mu_0} = \frac{5.14}{3.71} = 1.39$$

TABLE II (Continued)

MEASUREMENTS ON "WHITE VALLEY BOND" WITH CASTOR OIL

Sample: 1 sheet "White Valley Bond"

(g) Caliper = 0.00413 in. at 9.0 lb. per sq. in.

8-3 — $\bar{H} = 31.71$ $\bar{h} = 7.97$ $\mu_A = 5.34 \times 10^{-11}$ sq. cm.

The air was displaced by oil previous to placing the sample in the oil permeability instrument by coating the top side of the sheet with oil and allowing it to penetrate the sheet under capillary forces alone.

sec.	cc.	lb./sq.in.	η , poises	$\mu_0 \times 10^{11}$ sq. cm.
113.7	0.881	7.7	9.07	3.04
86.8	0.874	9.2	9.15	3.34
82.7	0.872	9.8	9.15	3.28
88.9	0.874	8.95	9.15	3.35
90.4	0.875	8.95	9.13	3.29
106.5	0.879	7.9	9.15	3.18
95.0	0.876	8.9	9.15	3.16
99.1	0.877	8.85	9.13	3.04

$$\frac{\mu_A}{\mu_0} = \frac{5.34}{3.35} = 1.59$$

(d) Caliper = 0.00419 in. at 9.0 lb. per sq. in.

0-3 — $\bar{H} = 32.00$ $\bar{h} = 6.33$ $\mu_A = 6.89 \times 10^{-11}$ sq. cm.

sec.	cc.	lb./sq. in.	η , poises	$\mu_0 \times 10^{11}$ sq. cm.
63.7	0.864	9.8	8.98	4.20
63.7	0.864	9.85	9.00	4.19
64.7	0.864	9.9	9.00	4.10
69.0	0.867	9.85	9.00	3.88
71.7	0.867	9.7	8.98	3.78
88.0	0.874	9.8	9.81	3.36
88.0	0.874	9.8	9.79	3.35
89.4	0.874	9.8	9.75	3.29
98.7	0.877	8.9	9.68	3.26
90.2	0.875	9.6	9.62	3.28
92.3	0.875	9.4	9.56	3.26
87.4	0.874	10.1	9.45	3.16
108.7	0.879	8.3	9.43	3.14
97.8	0.877	9.3	9.40	3.11
110.0	0.880	8.25	9.35	3.06
102.3	0.878	9.15	9.30	2.95

$$\frac{\mu_A}{\mu_0} = \frac{6.89}{4.27} = 1.61$$

TABLE III

MEASUREMENTS ON WHATMAN'S FILTER PAPER WITH CASTOR OIL

Sample: 6 sheets Whatman's Filter Paper No. 50

Caliper = 0.02754 in. at 19 lb. per sq. in

0-3 --- $\bar{H} = 22.79$ $\bar{h} = 11.81$ $\mu_A = 1.765 \times 10^{-10}$ sq. cm.

The sample was flushed with oil several times at 80 lb. prior to the first measurement to aid in displacing the air.

<u>sec.</u>	<u>cc.</u>	<u>lb./sq. in.</u>	<u>η, poises</u>	<u>$\mu_n \times 10^{10}$ sq. cm.</u>
67.2	0.866	20.4	8.90	1.250
66.1	0.865	20.2	8.86	1.278
73.3	0.868	19.0	8.84	1.224
70.5	0.867	19.2	8.81	1.255
72.1	0.868	19.0	8.81	1.240
72.0	0.868	19.05	8.80	1.238
68.8	0.866	20.15	9.08	1.263
74.0	0.869	19.0	8.98	1.233
75.0	0.869	19.0	8.98	1.217
71.4	0.867	19.6	9.00	1.241
72.7	0.868	19.3	9.00	1.237
71.0	0.867	19.9	8.97	1.225
66.0	0.865	22.7	9.45	1.213
74.2	0.869	20.0	9.42	1.203
74.0	0.869	20.2	9.40	1.215
84.5	0.873	17.6	9.33	1.217

$$\frac{\mu_A}{\mu_o} = \frac{1.765}{1.25} = 1.41$$

TABLE IV

MEASUREMENTS ON "WHITE VALLEY BOND" WITH VALVOLINE SAE 50

(a) Sample: 5 sheets "White Valley Bond"

Caliper = 0.01966 in. at 40 lb. per sq. in.

= 0.02001 in. at 20 lb. per sq. in.

C-3 --- $\bar{H} = 8.89$ $\bar{h} = 11.79$ $\mu_A = 5.11 \times 10^{-11}$ sq. cm.

Prior to the first measurement the sample was flushed with oil three times at 80 lb. to aid in displacing the air.

<u>sec.</u>	<u>cc.</u>	<u>lb./sq.in.</u>	<u>η, poises</u>	<u>$\mu_n \times 10^{11}$ sq. cm.</u>
121.6	0.890	21.6	5.66	3.10
67.8	0.882	39.0	5.63	2.98
64.7	0.881	40.8	5.63	2.98
*62.4	0.880	41.7	5.63	3.02
66.5	0.881	41.1	5.63	2.88
68.1	0.882	40.3	5.63	2.87
73.4	0.883	41.1	5.95	2.76
*72.0	0.883	40.9	5.89	2.80
*71.2	0.883	41.2	5.84	2.79

* indicates that the sample was flushed twice at 80 lb.

$$\frac{\mu_A}{\mu_o} = \frac{5.11}{3.02} = 1.69$$

(b) Sample: 3 sheets "White Valley Bond"

Caliper = 0.01235 in. at 19 lb. per sq. in

C-3 --- $\bar{H} = 16.70$ $\bar{h} = 12.03$ $\mu_A = 5.79 \times 10^{-11}$ sq. cm.

Prior to the first measurement the sample was flushed several times at 80 lb. to aid in displacing the air.

<u>sec.</u>	<u>cc.</u>	<u>lb./sq.in.</u>	<u>η, poises</u>	<u>$\mu_n \times 10^{11}$ sq. cm.</u>
68.3	0.882	19.25	5.66	3.79
64.7	0.881	20.85	5.63	3.66
66.4	0.882	21.0	5.64	3.60
69.0	0.882	20.4	5.66	3.54

$$\frac{\mu_A}{\mu_o} = \frac{5.79}{3.79} = 1.53$$

TABLE IV (continued)

MEASUREMENTS ON "WHITE VALLEY BOND" WITH VALVOLINE SAE 50

(c) Sample: 1 sheet "White Valley Bond"

Caliper = 0.00425 in. at 9.0 lb. per sq. in

C-3 --- $\bar{H} = 30.64$ $\bar{h} = 6.15$ $\mu_A = 6.91 \times 10^{-11}$ sq. cm.

<u>sec.</u>	<u>cc.</u>	<u>lb./sq.in.</u>	<u>η, poises</u>	<u>$\mu_o \times 10^{11}$ sq. cm.</u>
39.1	0.866	9.6	5.81	4.60
38.2	0.865	10.0	5.84	4.54
40.1	0.867	10.0	5.84	4.34
37.9	0.865	10.5	5.84	4.35
41.4	0.869	9.9	5.88	4.14

$$\frac{\mu_A}{\mu_o} = \frac{6.91}{4.60} = 1.50$$

TABLE V

MEASUREMENTS ON WHATMAN'S FILTER PAPER WITH VALVOLINE SAE 50

(a) Sample: 6 sheets Whatman's Filter Paper No. 50

Caliper = 0.02928 in. at 5.7 lb. per sq. in.

= 0.02872 in. at 9.0 lb. per sq. in.

= 0.02820 in. at 19 lb. per sq. in.

= 0.02785 in. at 40 lb. per sq. in.

<u>sec.</u>	<u>cc.</u>	<u>lb./sq.in</u>	<u>η, poises</u>	<u>$\mu_a \times 10^{10}$ sq. cm.</u>
*43.3	0.869	22.5	5.77	1.172
*95.3	0.887	10.15	5.77	1.228
*120.4	0.890	8.05	5.77	1.230
6575	0.910	0.187	6.04	1.035**
121.8	0.890	8.7	6.05	1.178
*100.4	0.888	10.0	6.05	1.239
* 99.6	0.888	10.0	6.10	1.260
* 97.4	0.888	10.2	6.02	1.248
*113.1	0.889	8.85	5.96	1.225
*107.1	0.889	9.3	5.91	1.222
207.8	0.895	4.85	5.89	1.236
102.8	0.888	9.85	5.86	1.192
69.2	0.882	14.15	5.84	1.210
53.5	0.876	18.70	5.84	1.163
193.8	0.894	5.2	5.83	1.222
99.5	0.888	9.3	5.82	1.295
68.6	0.882	14.85	5.82	1.160
*107.6	0.889	9.1	5.81	1.222

* indicates that the sample was flushed at 90 lb.

** indicates that the value of μ_0 is based on caliper at 9.0 lb. per sq. in.

<u>lb./sq.in.</u>	<u>$\mu_a \times 10^{10}$ sq. cm.</u>	<u>$\mu_0 \times 10^{10}$ sq. cm.</u>	<u>$\frac{\mu_a}{\mu_0}$</u>
5.7	1.850	1.229	1.51
9.0	1.813	1.231	1.47
15	1.799	1.190	1.51
19	1.781	1.163	1.53
0.187	1.813	1.035	1.75

TABLE V (continued)

MEASUREMENTS ON WHATMAN'S FILTER PAPER WITH VALVOLINE SAE 50

- (b) Sample: 1 sheet Whatman's Filter Paper No. 50
 Caliper = 0.00496 in. at 9.0 lb. per sq. in.
 C-4 — $\bar{h} = 10.75$ $\bar{h} = 11.72$ $\mu_A = 2.15 \times 10^{-10}$ sq. cm.

Prior to the first measurement the sample was flushed twice at 50 lb.

sec.	cc.	lb./sq.in.	η , poises	$\mu_o \times 10^{10}$ sq. cm.
875	0.899	0.187	5.68	1.247
862	0.899	0.187	5.70	1.270
918	0.899	0.187	5.72	1.200

$$\frac{\mu_A}{\mu_o} = \frac{2.15}{1.24} = 1.73$$

- (c) Sample: 12 sheets Whatman's Filter Paper No. 50
 Caliper = 0.05802 in. at 5.7 lb. per sq. in.
 = 0.05704 in. at 9.0 lb. per sq. in.
 = 0.05664 in. at 14.0 lb. per sq. in.
 = 0.05624 in. at 19 lb. per sq. in.
 = 0.05557 in. at 40 lb. per sq. in.

Prior to the first measurement the sample was flushed with oil several times at 100 lb. to aid in displacing the air.

sec.	cc.	lb./sq.in.	η , poises	$\mu_o \times 10^{10}$ sq. cm.
368.7	0.896	4.9	5.56	1.292
202.7	0.894	8.9	5.56	1.266
131.5	0.891	13.7	5.55	1.255
91.3	0.887	19.3	5.55	1.270
43.4	0.869	39.8	5.55	1.252
397.5	0.896	4.8	5.54	1.218
202.0	0.894	9.0	5.54	1.253
131.5	0.891	13.9	5.54	1.237
93.8	0.887	19.3	5.54	1.234
44.5	0.870	40.0	5.53	1.212

lb./sq.in.	$\mu_A \times 10^{10}$ sq. cm.	$\mu_o \times 10^{10}$ sq. cm.	$\frac{\mu_A}{\mu_o}$
5.7	1.913	1.255	1.52
9.0	1.881	1.259	1.49
14.0	1.870	1.246	1.50
19	1.857	1.252	1.48
40	1.833	1.232	1.49

TABLE VI

BEATER RUN NO. 1

(a) Sample: 17 sheets L-5"

Oil = Valvoline SAE 50

Caliper = 0.0775 in. at 5.7 lb. per sq. in.

C-3 --- $\underline{H} = 31.81$ $\underline{h} = 4.55$ $\mu_A = 1.760 \times 10^{-9}$ sq. cm.

Prior to the first measurement the sample was flushed with oil several times at 30 lb. to aid in displacing the air.

<u>sec.</u>	<u>cc.</u>	<u>lb./sq.in.</u>	<u>η, poises</u>	<u>$\mu \times 10^9$ sq. cm.</u>
47.6	0.872	5.4	5.77	1.227
43.4	0.870	5.8	5.78	1.249
44.3	0.870	5.79	5.79	1.251
48.1	0.872	5.2	5.81	1.270
40.0	0.866	6.5	5.81	1.212
41.5	0.868	6.1	5.81	1.247
47.1	0.872	5.5	5.81	1.225

$$\frac{\mu_A}{\mu_o} = \frac{1.760}{1.23} = 1.43$$

(b) Sample: 1 sheet L-20"

Oil: Valvoline SAE 50

Caliper = 0.00342 in. at 60 lb. per sq. in.

C-3 --- $\underline{H} = 8.54$ $\underline{h} = 11.74$ $\mu_A = 8.56 \times 10^{-12}$ sq. cm.

<u>sec.</u>	<u>cc.</u>	<u>lb./sq.in.</u>	<u>η, poises</u>	<u>$\mu \times 10^{12}$ sq. cm.</u>
43.2	0.869	61.7	5.91	5.31
45.6	0.871	60.9	5.91	5.11
45.7	0.871	62.5	5.91	4.97
48.5	0.873	61.1	5.91	4.80

$$\frac{\mu_A}{\mu_o} = \frac{8.56}{5.31} = 1.61$$

TABLE VII

BEATER RUN No. 2

(a) Sample: 23 sheets L-5"

Oil: Valvoline SAE 50

Caliper = 0.1108 in. at 9.0 lb. per sq. in.

C-3 --- $\bar{H} = 30.07$ $\bar{h} = 8.14$ $\mu_A = 1.338 \times 10^{-9}$ sq. cm.

<u>sec.</u>	<u>cc.</u>	<u>lb./sq.in.</u>	<u>η, poises</u>	<u>$\mu_0 \times 10^{10}$ sq. cm.</u>
*55.4	0.877	9.8	5.74	8.32
*53.1	0.876	9.95	5.76	8.56
*51.7	0.875	9.2	5.76	9.47
*53.6	0.876	9.0	5.76	9.36
*54.2	0.876	9.0	5.74	9.23
*63.2	0.880	7.9	5.74	9.15
*49.0	0.873	10.0	5.72	9.10
51.8	0.875	9.6	5.72	9.00
54.4	0.876	8.9	5.69	9.23
55.5	0.876	8.9	5.68	9.03

* indicates that the sample was flushed once at 50 lb.

$$\frac{\mu_A}{\mu_0} = \frac{1.338}{0.92} = 1.46$$

(b) Sample: 7 sheets L-10"

Oil: Valvoline SAE 50

Caliper = 0.0299 in. at 19 lb. per sq. in.

C-3 --- $\bar{H} = 13.54$ $\bar{h} = 10.95$ $\mu_A = 1.258 \times 10^{-10}$ sq. cm.

<u>sec.</u>	<u>cc.</u>	<u>lb./sq.in.</u>	<u>η, poises</u>	<u>$\mu_0 \times 10^{11}$ sq. cm.</u>
*75.8	0.884	19.9	5.71	8.08
*72.7	0.883	20.2	5.72	8.30
*80.9	0.885	18.65	5.72	8.11
*77.7	0.885	19.3	5.73	8.16
*75.6	0.884	20.0	5.75	8.12
83.4	0.886	18.8	5.75	7.85

* indicates that the sample was flushed once at 100 lb.

$$\frac{\mu_A}{\mu_0} = \frac{1.258}{0.830} = 1.52$$

TABLE VII (continued)

BEATNER HUM No. 2

(c) Sample: 7 sheets L-10"

Oil: Valvoline SAN 50

Caliper = 0.0287 in. at 19 lb. per sq. in.

0-3 --- $\bar{H} = 15.30$ $\bar{h} = 11.57$ $\mu_A = 1.247 \times 10^{-10}$ sq. cm.

sec.	cg.	lb./sq.in.	η , poises	$\mu_A \times 10^{11}$ sq. cm.
*72.1	0.883	18.9	5.72	8.57
*65.1	0.881	20.7	5.72	8.65
67.4	0.882	20.6	5.76	8.48
72.0	0.883	19.8	5.80	8.33
*75.9	0.884	18.65	5.80	8.40
76.0	0.884	19.8	5.82	7.93
78.2	0.885	19.5	5.80	7.80
*76.7	0.885	19.2	5.80	8.08

* indicates that the sample was flushed once at 100 lb.

$$\frac{\mu_A}{\mu_0} = \frac{1.247}{0.86} = 1.45$$

(d) Sample: 1 sheet L-15"

Oil: Valvoline SAN 50

Caliper = 0.00417 in. at 19 lb. per sq. in.

0-3 --- $\bar{H} = 18.04$ $\bar{h} = 11.51$ $\mu_A = 2.20 \times 10^{-11}$ sq. cm.

sec.	cg.	lb./sq.in.	η , poises	$\mu_A \times 10^{-11}$ sq. cm.
64.7	0.881	19.7	5.92	1.379
67.0	0.882	19.8	5.93	1.329
70.6	0.883	19.1	5.92	1.308
74.8	0.884	19.2	5.91	1.225
75.7	0.884	19.7	5.91	1.180
72.6	0.883	19.6	5.89	1.232
79.3	0.885	19.0	5.88	1.167
83.6	0.886	18.8	5.88	1.117
91.0	0.887	19.3	6.00	1.022
96.9	0.888	19.8	5.98	0.984
97.0	0.888	19.4	5.96	0.948

At this point the sample was washed six times with petroleum ether

0-3 --- $\bar{H} = 17.61$ $\bar{h} = 11.51$ $\mu_A = 2.15 \times 10^{-11}$ sq. cm.

62.8	0.880	19.6	5.78	1.392
66.6	0.882	19.3	5.78	1.338
70.6	0.883	19.1	5.78	1.273
71.0	0.883	19.5	5.76	1.238

$$\frac{\mu_A}{\mu_0} = \frac{2.20}{1.38} = 1.59$$

TABLE VII (continued)

BEATMR RUN No. 2

(e) Sample: 1 sheet L-20"

Oil: Valvoline SAE 50

Caliper = 0.00351 in. at 100 lb. per sq. in.

C-2 --- $\bar{h} = 25.84$ $\bar{h} = 11.87$ $\mu_A = 2.10 \times 10^{-12}$ sq. cm.

<u>sec.</u>	<u>cc.</u>	<u>lb./sq.in.</u>	<u>η, poises</u>	<u>$\mu_0 \times 10^{12}$ sq. cm.</u>
135.2	0.891	96.8	5.84	1.128
143.2	0.892	97.2	5.84	1.061
153.8	0.892	98.7	5.84	0.973
163.0	0.893	98.4	5.84	0.910

$$\frac{\mu_A}{\mu_0} = \frac{2.10}{1.20} = 1.75$$

(f) Sample: 1 sheet L-25"

Oil: Valvoline SAE 50

Caliper = 0.00329 in. at 100 lb. per sq. in.

C-2 --- $\bar{h} = 6.57$ $\bar{h} = 12.51$ $\mu_A = 4.81 \times 10^{-13}$ sq. cm.

<u>sec.</u>	<u>cc.</u>	<u>lb./sq.in.</u>	<u>η, poises</u>	<u>$\mu_0 \times 10^{13}$ sq. cm.</u>
755	0.898	97.9	5.76	1.86
970	0.900	98.1	5.76	1.45

$$\frac{\mu_A}{\mu_0} = \frac{4.81}{1.86} = 2.58$$

TABLE VIII
EFFECT OF PETROLEUM ETHER EXTRACTION
ON AIR AND OIL PERMEABILITY

Sample: 1 sheet L-15⁴—Beater Run No. 2

Oil: Valvoline SAE 50

Caliper = 0.00406 in. at 19 lb. per sq. in.

C-3 --- $\bar{H} = 14.92$ $\bar{h} = 11.19$ $\mu_A = 1.838 \times 10^{-11}$ sq. cm.

The sample stood under petroleum ether for 2 hr. and then μ_A redetermined.

C-3 --- $\bar{H} = 15.42$ $\bar{h} = 11.20$ $\mu_A = 1.893 \times 10^{-11}$ sq. cm.

Stood under petroleum ether for 12 hr. and then μ_A redetermined.

C-3 --- $\bar{H} = 16.32$ $\bar{h} = 11.67$ $\mu_A = 1.918 \times 10^{-11}$ sq. cm.

sec.	cc.	lb./sq.in.	η , poises	$\mu_o \times 10^{11}$ sq. cm.
70.9	0.883	19.95	5.89	1.203
70.0	0.883	20.9	5.91	1.170
78.1	0.883	20.05	5.91	1.093
89.1	0.887	18.7	5.91	1.030
94.0	0.887	18.8	5.90	0.971
93.5	0.887	19.2	5.90	0.923

$$\frac{\mu_A}{\mu_o} = \frac{1.918}{1.20} = 1.59$$

The oil was removed from the sample by washing four times with 20 cc. portions of petroleum ether.

C-3 --- $\bar{H} = 16.07$ $\bar{h} = 11.64$ $\mu_A = 1.894 \times 10^{-11}$ sq. cm.

The sample was washed again with 20 cc. of petroleum ether.

C-3 --- $\bar{H} = 16.06$ $\bar{h} = 11.62$ $\mu_A = 1.892 \times 10^{-11}$ sq. cm.

sec.	cc.	lb./sq.in.	η , poises	$\mu_o \times 10^{11}$ sq. cm.
78.6	0.885	18.6	5.82	1.154
76.1	0.884	19.55	5.83	1.133
74.0	0.884	20.9	5.84	1.093
86.5	0.886	19.1	5.83	1.024
93.5	0.887	18.5	5.83	0.980
96.1	0.887	19.0	5.83	0.929
97.2	0.888	19.6	5.83	0.890

$$\frac{\mu_A}{\mu_o} = \frac{1.892}{1.15} = 1.65$$

TABLE IX
EFFECT OF REVERSAL OF DIRECTION OF FLOW
ON OIL PERMEABILITY

Sample: 1 sheet L-20--Beater Run No. 1

Oil: Valvoline SAN 50

Caliper = 0.00368 in. at 40 lb. per sq. in.

= 0.00345 in. at 100 lb. per sq. in.

C-3 --- $\bar{h} = 7.48$ $\bar{h} = 12.01$ $\mu_A = 7.92 \times 10^{-12}$ sq. cm.

sec.	cc.	lb./sq.in.	η , poises	$\mu_o \times 10^{12}$ sq. cm.
78.2	0.885	39.8	5.82	4.79
81.5	0.885	41.0	5.82	4.59
89.4	0.887	39.4	5.82	4.36
101.6	0.888	39.7	6.06	3.97
***160.0	0.893	39.5	5.96	2.50
***236.3	0.895	39.2	5.89	1.69
61.4	0.879	98.9	6.16	2.46
183.2	0.894	39.5	6.12	2.25
205.6	0.894	39.0	6.10	2.02
66.9	0.882	98.7	6.07	2.26
67.5	0.882	97.9	6.06	2.25
68.1	0.882	98.4	6.04	2.21
67.9	0.882	99.8	6.02	2.18
203.7	0.894	39.4	6.02	1.995
220.7	0.894	39.8	5.98	1.81
255.2	0.895	38.0	5.98	1.64
81.7	0.885	98.7	5.96	1.823
83.3	0.885	97.5	5.95	1.807
83.7	0.885	98.6	5.93	1.767
85.3	0.886	98.8	5.93	1.737
At this point the sample was inverted				
35.7	0.863	99.0	5.78	3.93
37.4	0.864	101.0	5.78	3.68
104.4	0.888	39.4	5.78	3.70
109.0	0.889	40.8	5.80	3.45
*137.9	0.892	41.3	5.84	2.72
178.3	0.894	38.2	5.85	2.28
208.6	0.894	38.4	6.01	1.992

At this point the sample was reinverted

Each asterisk indicates that the sample was flushed once at 40 lb.

TABLE IX (continued)

EFFECT OF REVERSAL OF DIRECTION OF FLOW

ON OIL PERMEABILITY

<u>sec.</u>	<u>cc.</u>	<u>lb./sq.in.</u>	<u>η, poises</u>	<u>$\mu_o \times 10^{12}$ sq. cm.</u>
108.3	0.889	42.1	5.87	3.40
43.7	0.870	98.2	5.87	3.35
44.2	0.870	98.5	5.87	3.27
123.0	0.890	39.9	5.87	3.17
The sample was washed six times with petroleum ether to remove the oil.				
C-3 —	$\bar{H} = 7.25$	$\bar{h} = 12.13$	$\mu_A = 7.60 \times 10^{-12}$ sq. cm.	
82.7	0.885	39.8	5.89	4.71
84.5	0.886	41.0	5.91	4.49
96.3	0.888	39.2	5.91	4.13
*****217.0	0.894	38.5	6.16	1.96
233.4	0.895	39.5	6.46	1.86
At this point the sample was inverted.				
96.4	0.887	41.8	6.27	4.11
117.7	0.890	38.0	6.30	3.72
****175.5	0.893	41.1	6.25	2.30

Each asterisk indicates that the sample was flushed once at 40 lb.

The refractive index was examined during this test and was found to be unchanged (to within 0.0001) after the oil had passed through the sample.

TABLE X
MEASUREMENTS OF OIL PERMEABILITY
WITH BAYOJ

- (a) Sample: 10 sheets L-20--Beater Run No. 1
Oil: Bayoj (mineral oil free of unsaturates)
No absolute values of oil permeability were obtained.
 $\mu'_0 = \mu_0 \times k$, where k is an unknown constant.
Caliper is approximately 0.0036 in.
 $\mu_A = 8.5 \times 10^{-12}$ sq. cm.

<u>sec.</u>	<u>sq.</u>	<u>lb./sq.in.</u>	<u>η, poises</u>	<u>$\mu_0 \times 10^{12}$ sq. cm.</u>
90.0	0.887	17.2	6.03	1.004
81.4	0.886	19.0	6.06	1.002
78.0	0.886	20.0	6.08	1.003
86.1	0.887	17.9	6.06	1.013
***84.8	0.887	19.0	6.15	0.985
86.6	0.887	18.6	6.13	0.993
***82.5	0.886	19.9	6.18	0.969
87.8	0.887	18.7	6.16	0.967
***85.3	0.887	19.5	6.15	0.955
***87.3	0.887	19.1	6.10	0.944
***91.1	0.887	18.2	6.09	0.947

Each asterisk indicates that the sample was flushed once at 50 lb.

- (b) Sample: Rag content bond
Oil: Bayoj (a mineral oil free of unsaturates)
No absolute values of oil permeability were obtained.
 $\mu'_0 = \mu_0 \times k$, where k is an unknown constant.
Caliper is approximately 0.00400 in.
0-2 — $\underline{h} = 4.87$ $\underline{h} = 16.83$ $\mu_A = 3.25 \times 10^{-13}$ sq. cm.

<u>sec.</u>	<u>sq.</u>	<u>lb./sq.in.</u>	<u>η, poises</u>	<u>$\mu_0 \times 10^{14}$ sq. cm.</u>
74.1	0.884	38.9	6.06	6.00
85.2	0.886	39.7	6.01	5.09
96.8	0.887	39.4	6.02	4.53
109.2	0.889	39.6	6.02	4.00
164.3	0.893	38.3	6.33	2.91

TABLE XI

FILLER RUN NO. 1

(a) Sample: 1 sheet L-04--Filler Run No. 1

Oil: Valvoline SAE 50

Caliper = 0.00418 in. at 19 lb. per sq. in.

C-3 --- $\bar{H} = 17.22$ $\bar{h} = 11.99$ $\mu_A = 2.03 \times 10^{-11}$ sq. cm.

sec.	cc.	lb./sq.in.	n , poises	$\mu_0 \times 10^{11}$ sq. cm.
72.1	0.883	19.3	5.80	1.24
78.4	0.885	19.2	5.79	1.15
80.7	0.885	19.7	5.78	1.08
89.1	0.887	18.9	5.77	1.03
94.7	0.887	18.8	5.76	0.968

$$\frac{\mu_A}{\mu_0} = \frac{2.03}{1.24} = 1.63$$

(b) Sample: 1 sheet L-54--Filler Run No. 1

Oil: Valvoline SAE 50

Caliper = 0.00404 in. at 19 lb. per sq. in.

C-3 --- $\bar{H} = 19.05$ $\bar{h} = 11.78$ $\mu_A = 2.21 \times 10^{-11}$ sq. cm.

sec.	cc.	lb./sq.in.	n , poises	$\mu_0 \times 10^{11}$ sq. cm.
65.6	0.881	18.9	5.62	1.31
73.3	0.884	19.2	5.63	1.15
76.7	0.884	19.1	5.63	1.11
82.1	0.885	18.9	5.63	1.05

$$\frac{\mu_A}{\mu_0} = \frac{2.21}{1.31} = 1.69$$

(c) Sample: 1 sheet L-204--Filler Run No. 1

Oil: Valvoline SAE 50

Caliper = 0.00421 in. at 19 lb. per sq. in.

C-3 --- $\bar{H} = 30.71$ $\bar{h} = 11.66$ $\mu_A = 3.62 \times 10^{-11}$ sq. cm.

sec.	cc.	lb./sq.in.	n , poises	$\mu_0 \times 10^{11}$ sq. cm.
36.5	0.863	19.7	5.57	2.28
37.0	0.864	19.7	5.56	2.24
39.6	0.866	19.7	5.57	2.10
41.2	0.867	19.7	5.57	2.02

$$\frac{\mu_A}{\mu_0} = \frac{3.62}{2.28} = 1.59$$

TABLE XI (continued)

FILLER RUN NO. 1

(d) Sample: 1 sheet L-804--Filler Run No. 1

Oil: Valvoline SAN 50

Caliper = 0.00469 in. at 19 lb. per sq. in.

0-3 --- $\underline{H} = 30.88$ $\underline{h} = 11.93$ $\mu_A = 3.97 \times 10^{-11}$ sq. cm.

<u>sec.</u>	<u>cc.</u>	<u>lb./sq.in.</u>	<u>η, poises</u>	<u>$\mu \times 10^{11}$ sq. cm.</u>
39.3	0.866	20.0	5.72	2.38
43.3	0.869	19.3	5.71	2.25
44.0	0.869	19.2	5.71	2.22
45.5	0.870	19.7	5.72	2.10
47.0	0.871	19.7	5.72	2.04

$$\frac{\mu_A}{\mu_o} = \frac{3.97}{2.38} = 1.67$$

(e) Sample: 1 sheet L-2714--Filler Run No. 1

Oil: Valvoline SAN 50

Caliper = 0.00633 in. at 19 lb. per sq. in.

0-3 --- $\underline{H} = 31.26$ $\underline{h} = 10.79$ $\mu_A = 5.99 \times 10^{-11}$ sq. cm.

<u>sec.</u>	<u>cc.</u>	<u>lb./sq.in.</u>	<u>η, poises</u>	<u>$\mu \times 10^{11}$ sq. cm.</u>
40.6	0.866	19.1	5.62	3.21
39.7	0.866	19.8	5.63	3.17
43.7	0.869	19.1	5.63	2.99
43.2	0.869	19.9	5.63	2.91
46.0	0.870	19.2	5.63	2.83

$$\frac{\mu_A}{\mu_o} = \frac{5.99}{3.21} = 1.86$$

TABLE XII

SIZING RUN NO. 1

(a) Sample: 1 sheet L-04--Sizing Run No. 1

Oil: Valvoline SAE 50

Caliper = 0.00398 in. at 19 lb. per sq. in.

C-3 --- $\bar{H} = 18.47$ $\bar{h} = 11.56$ $\mu_A = 2.14 \times 10^{-11}$ sq. cm.

<u>sec.</u>	<u>cc.</u>	<u>lb./sq.in.</u>	<u>η, poises</u>	<u>$\mu \times 10^{11}$ sq. cm.</u>
63.7	0.881	19.7	5.93	1.34
69.7	0.882	19.0	5.93	1.27
72.0	0.883	19.5	5.93	1.20
80.7	0.885	18.0	5.91	1.16
81.3	0.885	18.6	5.90	1.11

$$\frac{\mu_A}{\mu_0} = \frac{2.14}{1.34} = 1.60$$

(b) Sample: 1 sheet L-14--Sizing Run No. 1

Oil: Valvoline SAE 50

Caliper = 0.00415 in. at 19 lb. per sq. in.

C-3 --- $\bar{H} = 19.47$ $\bar{h} = 11.26$ $\mu_A = 2.40 \times 10^{-11}$ sq. cm.

<u>sec.</u>	<u>cc.</u>	<u>lb./sq.in.</u>	<u>η, poises</u>	<u>$\mu \times 10^{11}$ sq. cm.</u>
55.6	0.877	19.7	5.81	1.56
58.8	0.879	19.7	5.84	1.48
65.2	0.881	18.7	5.84	1.41
64.7	0.881	19.6	5.84	1.36
71.9	0.883	18.6	5.84	1.29

$$\frac{\mu_A}{\mu_0} = \frac{2.40}{1.56} = 1.54$$

TABLE XII (continued)

SIZING RUN NO. 1

(g) Sample: 1 sheet L-27-Sizing Run No. 1

Oil: Valvoline SAE 50

Caliper = 0.00399 in. at 19 lb. per sq. in.

0-3 — $\bar{H} = 20.64$ $\bar{h} = 10.88$ $\mu_A = 2.54 \times 10^{-11}$ sq. cm.

<u>sec.</u>	<u>cc.</u>	<u>lb./sq.in.</u>	<u>η, poises</u>	<u>$\mu \times 10^{11}$ sq. cm.</u>
51.6	0.875	18.8	5.84	1.69
58.3	0.878	17.8	5.86	1.60
57.7	0.878	18.8	5.87	1.52
60.6	0.879	18.4	5.87	1.48
58.4	0.878	19.8	5.87	1.43

$$\frac{\mu_A}{\mu} = \frac{2.54}{1.69} = 1.50$$

(d) Sample: 1 sheet L-47-Sizing Run No. 1

Oil: Valvoline SAE 50

Caliper = 0.00423 in. at 19 lb. per sq. in.

0-3 — $\bar{H} = 27.55$ $\bar{h} = 10.58$ $\mu_A = 3.55 \times 10^{-11}$ sq. cm.

<u>sec.</u>	<u>cc.</u>	<u>lb./sq.in.</u>	<u>η, poises</u>	<u>$\mu \times 10^{11}$ sq. cm.</u>
40.5	0.867	18.4	5.91	2.31
40.5	0.867	18.8	5.93	2.26
39.2	0.867	19.8	5.93	2.22
41.3	0.868	19.2	5.93	2.17
40.4	0.867	20.2	5.93	2.11

$$\frac{\mu_A}{\mu} = \frac{3.55}{2.31} = 1.54$$

TABLE XIII

BEATER RUN NO. 3

(a) Sample: 20 sheets L-2¹--Beater Run No. 3

Oil: Valvoline SAN 50

Caliper = 0.1160 in. at 5.7 lb. per sq. in.

= 0.1129 in. at 9.0 lb. per sq. in.

= 0.1100 in. at 14 lb. per sq. in.

= 0.1070 in. at 19 lb. per sq. in.

C-3 ---	H = 4.61	h = 2.00	$\mu_A = 9.13 \times 10^{-10}$	sq. cm.
C-3 ---	H = 9.29	h = 4.01	$\mu_A = 9.08 \times 10^{-10}$	sq. cm.
C-3 ---	H = 14.39	h = 6.07	$\mu_A = 9.15 \times 10^{-10}$	sq. cm.
C-3 ---	H = 19.33	h = 8.09	$\mu_A = 9.11 \times 10^{-10}$	sq. cm.
C-3 ---	H = 24.53	h = 10.10	$\mu_A = 9.10 \times 10^{-10}$	sq. cm.
C-3 ---	H = 29.71	h = 12.07	$\mu_A = 9.10 \times 10^{-10}$	sq. cm.

sec.	cc.	lb./sq.in.	η , poises	$\mu_A \times 10^{10}$	sq. cm.
*104.9	0.859	8.8	5.75	5.05	
* 94.3	0.827	8.9	5.74	5.55	
* 78.5	0.885	9.6	5.70	6.11	
* 76.6	0.884	9.65	5.68	6.19	
* 77.1	0.884	9.6	5.70	6.21	
* 78.0	0.885	9.5	5.72	6.23	
* 78.7	0.885	9.6	5.72	6.11	
* 78.5	0.885	9.5	5.70	6.16	
158.6	0.893	4.8	5.71	6.27	
82.4	0.886	9.0	5.66	6.17	
51.8	0.875	14.1	5.66	6.02	
37.6	0.865	19.7	5.66	5.72	
148.8	0.892	5.0	5.63	6.32	
83.9	0.886	8.7	5.62	6.22	
52.5	0.875	13.9	5.60	5.97	
37.6	0.865	19.3	5.59	5.76	
156.3	0.892	4.8	5.60	6.31	
84.8	0.886	8.7	5.59	6.14	
52.5	0.875	14.1	5.59	5.88	
37.7	0.865	19.4	5.59	5.71	

* indicates that the sample was flushed once at 50 lb.

$$\frac{\mu_A}{\mu_0} = \frac{9.10}{6.17} = 1.47$$

TABLE XIII (continued)

BEATER RUN NO. 3

- (b) Sample: 12 sheets L-6"---Beater Run No. 3
 Oil: Valvoline SAE 50
 Caliper = 0.0610 in. at 9.0 lb. per sq. in.
 0-3 --- $\bar{H} = 21.81$ $\bar{h} = 9.85$ $\mu_A = 4.52 \times 10^{-10}$ sq. cm.

<u>sec.</u>	<u>cc.</u>	<u>lb./sq.in.</u>	<u>n, poises</u>	<u>$\mu \times 10^{10}$ sq. cm.</u>
*103.2	0.888	8.9	5.59	2.66
* 94.7	0.887	8.4	5.59	3.07
* 90.3	0.887	8.7	5.58	3.10
* 87.8	0.886	9.1	5.55	3.03
* 90.0	0.887	9.0	5.54	2.99
* 87.7	0.886	9.3	5.52	2.96
84.8	0.886	9.5	5.50	2.98
87.3	0.886	9.5	5.49	2.89
86.8	0.886	9.5	5.47	2.89
83.6	0.886	9.7	5.47	2.94
86.1	0.886	9.5	5.46	2.91

* indicates that the sample was flushed once at 80 lb.

$$\frac{\mu_A}{\mu_0} = \frac{4.52}{3.10} = 1.46$$

- (c) Sample: 5 sheets L-11"---Beater Run No. 3
 Oil: Valvoline SAE 50
 Caliper = 0.0237 in. at 9.0 lb. per sq. in.
 0-3 --- $\bar{H} = 21.44$ $\bar{h} = 9.87$ $\mu_A = 1.80 \times 10^{-10}$ sq. cm.

<u>sec.</u>	<u>cc.</u>	<u>lb./sq.in.</u>	<u>n, poises</u>	<u>$\mu \times 10^{10}$ sq. cm.</u>
*103.6	0.888	7.7	5.25	1.17
* 89.5	0.887	8.9	5.25	1.17
* 90.5	0.887	9.5	5.27	1.09
* 95.0	0.887	8.8	5.27	1.12
95.9	0.887	9.2	5.28	1.06
98.7	0.888	9.1	5.30	1.05
99.1	0.888	9.3	5.31	1.02
100.2	0.888	9.4	5.30	0.997

* indicates that the sample was flushed once at 80 lb.

$$\frac{\mu_A}{\mu_0} = \frac{1.80}{1.17} = 1.54$$

TABLE XIII (continued)

BEATER RUN NO. 3

- (d) Sample: 2 sheets L-15"---Beater Run No. 3
 Oil: Valvoline SAE 50
 Caliper = 0.00920 in. at 9.0 lb. per sq. in.
 G-3 --- $\bar{H} = 29.07$ $\bar{h} = 9.13$ $\mu_A = 9.66 \times 10^{-11}$ sq. cm.

<u>sec.</u>	<u>cc.</u>	<u>lb./sq.in.</u>	<u>η, poises</u>	<u>$\mu \times 10^{11}$ sq. cm.</u>
*69.2	0.882	9.0	5.54	5.84
*70.6	0.882	9.1	5.52	5.63
*67.8	0.882	9.8	5.50	5.43
*73.1	0.883	9.3	5.47	5.28
*73.2	0.883	9.3	5.46	5.26
*78.6	0.883	8.7	5.44	5.24
82.7	0.886	8.7	5.44	4.98
83.8	0.886	8.9	5.42	4.79
86.4	0.886	8.8	5.42	4.70
85.5	0.886	9.3	5.42	4.49
86.4	0.887	9.2	5.41	4.48

* indicates that the sample was flushed once at 80 lb.

$$\frac{\mu_A}{\mu_o} = \frac{9.66}{5.84} = 1.65$$

- (e) Sample: 1 sheet L-20"---Beater Run No. 3
 Oil: Valvoline SAE 50
 Caliper = 0.00451 in. at 9.0 lb. per sq. in.
 G-3 --- $\bar{H} = 27.86$ $\bar{h} = 9.80$ $\mu_A = 4.22 \times 10^{-11}$ sq. cm.

<u>sec.</u>	<u>cc.</u>	<u>lb./sq.in.</u>	<u>η, poises</u>	<u>$\mu \times 10^{11}$ sq. cm.</u>
83.7	0.886	8.9	5.55	2.40
86.2	0.886	9.5	5.57	2.20
94.6	0.887	9.1	5.55	2.08
100.3	0.888	9.1	5.55	1.97
108.6	0.889	9.0	5.55	1.84
115.1	0.890	8.85	5.55	1.76

$$\frac{\mu_A}{\mu_o} = \frac{4.22}{2.40} = 1.76$$

TABLE XIV

FILLER RUN NO. 2

(a) Sample: 1 sheet L-04--Filler Run No. 2

Oil: Valvoline SAE 50

Caliper = 0.00393 in. at 40 lb. per sq. in.

0-3 --- $\bar{h} = 7.60$ $h = 11.13$ $\mu_A = 9.31 \times 10^{-12}$ sq. cm.

sec.	cc.	lb./sq.in.	η , poises	$\mu_a \times 10^{12}$ sq. cm.
67.0	0.882	39.9	5.54	5.81
70.6	0.883	40.4	5.54	5.44
75.7	0.884	40.1	5.54	5.12
76.5	0.884	41.3	5.54	4.92
83.5	0.886	40.2	5.54	4.64

$$\mu_A = \frac{9.31}{5.81} = 1.60$$

(b) Sample: 1 sheet L-54--Filler Run No. 2

Oil: Valvoline SAE 50

Caliper = 0.00399 in. at 40 lb. per sq. in.

0-3 --- $\bar{h} = 9.18$ $h = 10.75$ $\mu_A = 10.8 \times 10^{-12}$ sq. cm.

sec.	cc.	lb./sq.in.	η , poises	$\mu_a \times 10^{12}$ sq. cm.
53.8	0.876	41.3	5.68	7.22
56.1	0.877	40.9	5.70	7.04
56.9	0.877	42.1	5.70	6.73
64.7	0.881	38.9	5.68	6.41
62.7	0.880	40.9	5.68	6.27

$$\mu_A = \frac{10.8}{7.22} = 1.50$$

(c) Sample: 1 sheet L-204--Filler Run No. 2

Oil: Valvoline SAE 50

Caliper = 0.00414 in. at 40 lb. per sq. in.

0-3 --- $\bar{h} = 12.83$ $h = 10.30$ $\mu_A = 1.77 \times 10^{-11}$ sq. cm.

sec.	cc.	lb./sq.in.	η , poises	$\mu_a \times 10^{11}$ sq. cm.
37.1	0.865	41.0	5.76	1.10
39.0	0.866	40.1	5.76	1.07
40.4	0.867	40.1	5.76	1.03
41.2	0.867	40.2	5.76	1.01
43.4	0.868	39.9	5.76	0.965

$$\mu_A = \frac{1.77}{1.10} = 1.61$$

TABLE XIV (continued)

FILLER RUN NO. 2

(d) Sample: 1 sheet L-807--Filler Run No. 2

Oil: Valvoline SAE 50

Caliper = 0.00306 in. at 19 lb. per sq. in.

C-3 --- $\bar{H} = 26.54$ $\bar{h} = 9.40$ $\mu_A = 4.73 \times 10^{-11}$ sq. cm.

<u>sec.</u>	<u>cc.</u>	<u>lb./sq.in.</u>	<u>n, poises</u>	<u>$\mu \times 10^{11}$ sq. cm.</u>
35.2	0.863	19.5	5.72	2.94
35.5	0.863	19.8	5.72	2.87
37.3	0.864	19.7	5.72	2.75
39.6	0.866	19.0	5.72	2.69
37.3	0.864	20.1	5.72	2.69
39.8	0.866	19.3	5.70	2.62

$$\frac{\mu_A}{\mu_0} = \frac{4.73}{2.94} = 1.61$$

(e) Sample: 1 sheet L-3127--Filler Run No. 2

Oil: Valvoline SAE 50

Caliper = 0.00983 in. at 9.0 lb. per sq. in.

C-3 --- $\bar{H} = 33.69$ $\bar{h} = 2.57$ $\mu_A = 4.20 \times 10^{-10}$ sq. cm.

<u>sec.</u>	<u>cc.</u>	<u>lb./sq. in.</u>	<u>n, poises</u>	<u>$\mu \times 10^{10}$ sq. cm.</u>
29.0	0.856	5.2	5.65	2.55
27.0	0.855	5.8	5.65	2.45
31.2	0.859	5.0	5.65	2.46
33.8	0.861	4.8	5.65	2.38
31.5	0.859	5.2	5.65	2.35

$$\frac{\mu_A}{\mu_0} = \frac{4.20}{2.59} = 1.62$$

All calculations based on caliper at 9.0 lb. per sq. in.

TABLE XV

THE EFFECT OF ANTI-OXIDANT
ON OIL PERMEABILITY

Sample: 1 sheet L-07—Filler Run No. 2

Oil: Valvoline SAE 50 to which about 0.01% of monobenzyl-p-aminophenol
(in isopropyl alcohol solution) had been added.

Caliper = 0.00376 in. at 40 lb. per sq. in.

0-3 — $\bar{h} = 8.93$ $\bar{h} = 12.14$ $\mu_A = 9.56 \times 10^{-12}$ sq. cm.

<u>sec.</u>	<u>cc.</u>	<u>lb./sq.in.</u>	<u>η, poises</u>	<u>$\mu \times 10^{12}$ sq. cm.</u>
63.0	0.880	39.6	5.78	6.19
68.8	0.882	39.9	5.77	5.64
78.4	0.885	39.6	5.76	4.99
85.6	0.886	40.0	5.76	4.53
98.9	0.888	39.2	5.75	4.01

$$\frac{\mu_A}{\mu_o} = \frac{9.56}{6.19} = 1.55$$

These data are to be compared with those of Table XIV
(a). It is apparent that the addition of antioxidant to the oil has caused the decrease in oil permeability, as successive measurements are made, to be much more pronounced. It was suspected that, when a few cc. of an isopropyl alcohol solution of monobenzyl-p-aminophenol were added to several hundred cc. of mineral oil, the monobenzyl-p-aminophenol might not remain in true solution but might separate in the form of colloidal particles suspended in the oil. Samples of the oil both with and without antioxidant were examined in a strong beam of light. The pure oil showed very little scattering of light, whereas the oil to which antioxidant had been added exhibited considerable scattering of light. Solid particles, presumably of the antioxidant, could actually be distinguished visually. It is probable that the filtering out of these particles from the oil as it passed through the sample caused the more pronounced decrease in oil permeability which was observed as successive measurements were made.

TABLE XVI

SIZING RUN NO. 2

(a) Sample: 1 sheet L-048--Sizing Run No. 2

Oil: Valvoline SAE 50

Caliper = 0.00389 in. at 40 lb. per sq. in.

C-3 --- $\bar{h} = 7.97$ $\bar{h} = 11.98$ $\mu_A = 8.99 \times 10^{-12}$ sq. cm.

sec.	cc.	lb./sq.in.	η , poises	$\mu_A \times 10^{12}$ sq. cm.
79.2	0.885	39.5	5.72	5.08
85.3	0.886	39.3	5.72	4.75
86.9	0.886	40.3	5.73	4.56
89.4	0.887	40.7	5.73	4.39
100.0	0.888	39.2	5.72	4.07

$$\frac{\mu_A}{\mu_0} = \frac{8.99}{5.08} = 1.77$$

(b) Sample: 1 sheet L-248--Sizing Run No. 2

Oil: Valvoline SAE 50

Caliper = 0.00404 in. at 40 lb. per sq. in.

C-3 --- $\bar{h} = 5.88$ $\bar{h} = 11.70$ $\mu_A = 7.08 \times 10^{-12}$ sq. cm.

sec.	cc.	lb./sq.in.	η , poises	$\mu_A \times 10^{12}$ sq. cm.
103.5	0.888	39.4	5.63	4.00
106.6	0.888	40.9	5.64	3.75
123.7	0.890	38.2	5.63	3.46
118.1	0.890	40.6	5.63	3.41
127.7	0.890	40.3	5.63	3.18

$$\frac{\mu_A}{\mu_0} = \frac{7.08}{4.00} = 1.77$$

(c) Sample: 1 sheet L-448--Sizing Run No. 2

Oil: Valvoline SAE 50

Caliper = 0.00424 in. at 40 lb. per sq. in.

C-3 --- $\bar{h} = 8.10$ $\bar{h} = 11.68$ $\mu_A = 10.2 \times 10^{-12}$ sq. cm.

sec.	cc.	lb./sq.in.	η , poises	$\mu_A \times 10^{12}$ sq. cm.
65.6	0.881	40.5	5.68	6.45
71.5	0.883	40.1	5.67	5.99
74.5	0.884	40.0	5.67	5.76
75.0	0.884	40.3	5.67	5.69
80.6	0.885	39.8	5.67	5.36

$$\frac{\mu_A}{\mu_0} = \frac{10.2}{6.45} = 1.58$$

TABLE XVI (continued)

SIZING RUN NO. 2

(d) Sample: 1 sheet L-54S--Sizing Run No. 2

Oil: Valvoline SAE 50

Caliper = 0.00417 in. at 40 lb. per sq. in.

C-3 --- $\underline{H} = 6.99$ $\underline{h} = 11.82$ $\mu_A = 8.60 \times 10^{-12}$ sq. cm.

<u>sec.</u>	<u>cc.</u>	<u>lb./sq.in.</u>	<u>η, poises</u>	<u>$\mu \times 10^{12}$ sq. cm.</u>
75.5	0.884	39.3	5.61	5.64
78.3	0.885	40.1	5.63	5.35
80.4	0.885	40.3	5.63	5.19
84.8	0.886	40.1	5.64	4.95
88.4	0.886	40.3	5.64	4.72

$$\frac{\mu_A}{\mu_0} = \frac{8.60}{5.64} = 1.52$$

(e) Sample: 1 sheet L-44S, 44R--Sizing Run No. 2

Oil: Valvoline SAE 50

Caliper = 0.00446 in. at 40 lb. per sq. in.

C-3 --- $\underline{H} = 6.22$ $\underline{h} = 11.89$ $\mu_A = 8.13 \times 10^{-12}$ sq. cm.

<u>sec.</u>	<u>cc.</u>	<u>lb./sq.in.</u>	<u>η, poises</u>	<u>$\mu \times 10^{12}$ sq. cm.</u>
91.8	0.887	39.6	5.64	4.96
95.1	0.888	39.6	5.64	4.79
100.0	0.888	40.1	5.64	4.50
113.3	0.889	38.3	5.66	4.17
110.0	0.889	40.9	5.66	4.03

$$\frac{\mu_A}{\mu_0} = \frac{8.13}{4.96} = 1.64$$

TABLE XVII
STUDY OF THE FILTRATION EFFECT
USING VALVOLINE SAE 50

- (a) Sample: 1 sheet "White Valley Bond"
Caliper = 0.00416 in. at 9.0 lb. per sq. in.
C-3 — $\bar{h} = 29.70$ $\bar{h} = 7.33$ $\mu_A = 5.04 \times 10^{-11}$ sq. cm.
- (b) Sample: 1 sheet "White Valley Bond"
Caliper = 0.00418 in. at 9.0 lb. per sq. in.
C-3 — $\bar{h} = 30.96$ $\bar{h} = 6.38$ $\mu_A = 6.44 \times 10^{-11}$ sq. cm.
- (c) Sample: 1 sheet "White Valley Bond"
Caliper = 0.00415 in. at 9.0 lb. per sq. in.
C-3 — $\bar{h} = 30.50$ $\bar{h} = 7.19$ $\mu_A = 5.77 \times 10^{-11}$ sq. cm.
- (d). (b), (c) The three sheets were placed in series with (a) on top and (c) on the bottom and, without wax-sealing the edges, oil permeability measurements were made. Caliper was taken as 0.0125 in. at 19 lb. per sq. in.

sec.	sq.	lb./sq.in.	η , poises	$\mu_a \times 10^{11}$ sq. cm.
70.0	0.883	19.2	5.74	3.81
73.0	0.884	19.2	5.74	3.66
66.0	0.882	21.4	5.74	3.61
80.3	0.883	17.9	5.76	3.58
75.5	0.884	19.0	5.75	3.58
183.0	0.893	8.2	5.74	3.45
180.7	0.893	8.95	5.72	3.19
183.8	0.893	9.0	5.68	3.10
191.3	0.893	8.9	5.67	3.01
81.2	0.883	19.2	5.63	3.22
86.5	0.886	18.6	5.62	3.13
196.3	0.894	8.5	5.61	3.04
85.5	0.886	19.2	5.60	3.05
95.5	0.887	19.1	6.09	2.99

The three sheets were taken out of the air permeability instrument and their oil permeabilities measured separately.

TABLE XVII (continued)
STUDY OF THE FILTRATION EFFECT
USING VALVOLINE SAE 50

(a)

<u>sec.</u>	<u>cc.</u>	<u>lb./sq.in.</u>	<u>η, poises</u>	<u>$\mu_o \times 10^{11}$ sq. cm.</u>
30.0	0.858	20.2	5.96	2.84
71.0	0.883	9.0	5.91	2.75
72.6	0.883	9.2	5.93	2.64
75.7	0.884	9.1	5.92	2.55
76.1	0.884	9.3	5.89	2.47

$$\frac{\mu_A}{\mu_o} = \frac{5.04}{2.82} = 1.79$$

(b)

<u>sec.</u>	<u>cc.</u>	<u>lb./sq.in.</u>	<u>η, poises</u>	<u>$\mu_o \times 10^{11}$ sq. cm.</u>
47.5	0.873	9.6	5.81	3.75
51.3	0.874	9.0	5.81	3.71
48.9	0.873	9.6	5.81	3.64
52.7	0.874	9.4	5.81	3.46
52.4	0.874	9.5	5.78	3.42

$$\frac{\mu_A}{\mu_o} = \frac{6.44}{3.75} = 1.72$$

(c)

<u>sec.</u>	<u>cc.</u>	<u>lb./sq.in.</u>	<u>η, poises</u>	<u>$\mu_o \times 10^{11}$ sq. cm.</u>
50.0	0.874	9.7	5.68	3.43
52.3	0.875	9.4	5.70	3.40
52.9	0.875	9.4	5.70	3.36
54.8	0.877	9.3	5.70	3.29
57.5	0.878	9.2	5.70	3.17

$$\frac{\mu_A}{\mu_o} = \frac{5.77}{3.43} = 1.68$$

The three samples were washed with petroleum ether to remove the oil and the air and oil permeabilities were redetermined.

TABLE XVII (continued)
STUDY OF THE FILTRATION EFFECT
USING VALVOLINE SAE 50

(a) 0-3 — $\underline{H} = 30.69$ $\underline{h} = 7.98$ $\mu_A = 5.24 \times 10^{-11}$ sq. cm.

<u>sec.</u>	<u>cc.</u>	<u>lb./sq.in.</u>	<u>η, poises</u>	<u>$\mu \times 10^{11}$ sq. cm.</u>
53.6	0.876	9.6	6.02	3.44
57.4	0.878	9.0	6.02	3.44
59.4	0.879	8.9	6.02	3.36
56.7	0.878	9.6	6.00	3.25
63.5	0.881	8.9	5.99	3.14

$$\frac{\mu_A}{\mu_0} = \frac{5.24}{3.44} = 1.52$$

(b) 0-3 — $\underline{H} = 30.82$ $\underline{h} = 6.68$ $\mu_A = 6.31 \times 10^{-11}$ sq. cm.

<u>sec.</u>	<u>cc.</u>	<u>lb./sq.in.</u>	<u>η, poises</u>	<u>$\mu \times 10^{11}$ sq. cm.</u>
44.4	0.870	9.3	5.92	4.21
47.0	0.872	9.0	5.94	4.13
48.3	0.873	8.9	5.93	4.06
49.6	0.874	9.1	5.93	3.97
51.1	0.875	9.0	5.93	3.80

$$\frac{\mu_A}{\mu_0} = \frac{6.31}{4.21} = 1.50$$

(c) 0-3 — $\underline{H} = 30.67$ $\underline{h} = 7.45$ $\mu_A = 5.60 \times 10^{-11}$ sq. cm.

<u>sec.</u>	<u>cc.</u>	<u>lb./sq.in.</u>	<u>η, poises</u>	<u>$\mu \times 10^{11}$ sq. cm.</u>
48.8	0.874	8.5	5.87	3.71
52.4	0.875	8.9	5.88	3.70
53.0	0.875	9.0	5.88	3.61
53.7	0.875	9.3	5.88	3.45
56.4	0.877	9.0	5.88	3.40

$$\frac{\mu_A}{\mu_0} = \frac{5.60}{3.71} = 1.51$$

TABLE XVIII

THE EFFECT OF DISTILLATION OF THE VALVOLINE SAE 50
ON OIL PERMEABILITY MEASUREMENTS

Sample: 1 sheet L-25^u--Beater Run No. 2
Oil: Distilled Valvoline SAE 50 --- distillation range = 110° to 180° C. in the molecular still.
Caliper = 0.00314 in. at 100 lb. per sq. in.
C-3 --- $\bar{H} = 4.00$ $\bar{h} = 10.97$ $\mu_A = 3.22 \times 10^{-13}$ sq. cm.

<u>sec.</u>	<u>cc.</u>	<u>lb./sq. in.</u>	<u>η, poises</u>	<u>$\mu \times 10^{14}$ sq. cm.</u>
227.5	0.895	98.0	5.80	5.90
260.0	0.895	97.7	5.81	5.19
284.0	0.895	97.5	5.82	4.77
306.2	0.895	97.4	5.82	4.44

$\mu'_0 = \mu_0 \times k$, where k is an unknown constant.

TABLE XIX

PHYSICAL DATA FOR BEATER RUN NO. 1

Stock: West coast bleached sulfite

<u>Sample identi- fication</u>	<u>Beating time, min.</u>	<u>Freeness cc. S.-R.</u>	<u>Basis wt.lb. 25x40-- 500</u>	<u>Burst, points per lb.</u>	<u>Tear factor</u>
L-5 ^u	5	830	43.2	0.372	2.59
L-20 ^u	20	430	43.9	0.773	1.33

TABLE XX

PHYSICAL DATA FOR BEATER RUN NO. 2

STOCK: West coast bleached sulfite

Sample identi- fication	Beating time, min.	Free- ness cc. S.-R.	Basis wt.lb. 25x40-- 500	Burst, points per lb.	Tear factor	Gurley porosity, sec.	Fuss oil penetra- tion sec.	I.P.C. oil penetra- tion*
L-5"	5	610	47.3	0.376	2.76	1.9	11.1	-----
L-10"	10	670	49.3	0.682	1.84	17.2	43	0.16
L-15"	15	460	48.1	0.798	1.46	94.6	186	0.054
L-20"	20	310	47.4	0.832	1.16	260	1170	-----
L-25"	25	200	-----	-----	-----	-----	-----	-----

* Rate of penetration of castor oil in mils per sec. at a depth of 2 mils.

TABLE XXI

PHYSICAL DATA FOR FILLER RUN NO. 1

Stock: West coast bleached sulfite beaten for 17 min. to a freeness of 450 cc. S.-R.

Clay: English coating clay

Sample identi- fication	Basis wt.lb. 25x40-- 500	Clay in sheet, %	Burst, points per lb.	Tear factor	Gurley porosity, sec.	Fuss oil penetra- tion sec.	I.P.C. oil penetra- tion*
L-0%	47.6	0	0.867	1.54	101	148	0.0049
L-5%	48.6	2.1	0.845	1.52	74	170	0.0036
L-20%	50.4	5.8	0.712	1.55	57	142	0.0055
L-80%	58.0	21.8	0.505	1.47	58	119	0.0114
L-271%	88.2	85.3	0.172	0.83	62	151	0.160

* Rate of penetration of castor oil in mils per sec. at a depth of 2 mils.

TABLE XXII

PHYSICAL DATA FOR SIZING RUN NO. 1

Stock: West coast bleached sulfite beaten for 15-1/2 min. to a freeness of 450 cc. S.-R.
 Size: Rosin size --- 30% free rosin
 Alum: pH adjusted to about 4.7 with alum

Sample identi- fication	Size added, %	Basis wt.lb. 25x40--- 500	Burst, points per lb.	Tear factor	Gurley porosity, sec.	Fuess oil penetra- tion	I.P.C. oil penetra- tion*
L-0%	0	47.6	0.817	1.40	86	190	0.049
L-1%	1	50.6	0.713	1.46	78	204	0.053
L-2%	2	51.1	0.729	1.46	67	204	0.056
L-4%	4	51.3	0.644	1.44	48	167	0.078

* Rate of penetration of castor oil in mils per sec. at a depth of 2 mils.

TABLE XXIII

PHYSICAL DATA FOR BEATER RUN NO. 3

Stock: Hardwood bleached kraft

Sample identi- fication	Beating time, min.	Freeness cc. S.-R.	Basis wt.lb. 25x40--- 500	Burst, Points per lb.	Tear factor	Gurley porosity, sec.	Fuess oil penetra- tion	I.P.C. oil penetra- tion*
L-2"	2	705	44.2	0.170	0.560	3.8	16.8	-----
L-6"	6	620	44.3	0.212	0.531	6.9	23.4	-----
L-11"	11	440	44.7	0.248	0.447	15.6	39.0	0.186
L-15"	15	350	42.4	0.274	0.441	28.9	63.0	0.140
L-20"	20	230	44.6	0.296	0.419	57.3	142	0.024

* Rate of penetration of castor oil in mils per sec. at a depth of 2 mils.

TABLE XXIV

PHYSICAL DATA FOR FILLER RUN NO. 2

Stock: West coast bleached sulfite beaten to 390 cc. S.-R.
 Filler: Cameline Whiting—98.50% CaCO_3 , 99.75% through 325 mesh

Sample identi- fication	Basis wt.lb. 25x40— 500	CaCO_3 in sheet, %	Burst, points per lb.	Tear factor	Gurley porosity, sec.	Fuess oil penetra- tion	I.P.C. oil penetra- tion*
L-0%	45.7	0	0.817	1.21	164	400	0.024
L-5%	48.3	5.7	0.786	1.23	145	332	0.030
L-20%	50.5	10.5	0.765	1.27	127	263	0.045
L-80%	60.4	32.2	0.546	1.20	53	106	0.123
L-312%	133.9	193.	0.110	0.64	12.6	67	—

* Rate of penetration of castor oil in mils per sec. at a depth of 2 mils.

TABLE XXV

PHYSICAL DATA FOR SIZING RUN NO. 2

Stock: West coast bleached sulfite beaten to 400 cc. S.-R.
 Size: Starch size — 25 g. tapioca starch mixed with 400 cc. water,
 temperature brought up to 90° C. with direct steam in 30 min.,
 maintained at 90° C. for 15 min.

Sample identi- fication	Size added, %	Basis wt.lb. 25x40— 500	Burst, points per lb.	Tear factor	Gurley porosity, sec.	Fuess oil penetra- tion	I.P.C. oil penetra- tion*
L-0%	0	46.7	0.800	1.31	140	391	0.0214
L-2%	2	49.1	1.01	1.16	183	435	0.1250
L-4%	4	50.0	1.06	1.09	153	409	0.0275
L-8%	8	52.0	1.04	0.966	152	436	0.0378
**L-4% 4%R	-	55.5	0.638	1.16	150	710	—

* Rate of penetration of castor oil in mils per sec. at a depth of 2 mils.

** This batch of handsheets was sized with 4% rosin (30% free rosin) and 4% starch, and the pH was adjusted to 4.7 with alum.

These handsheets were dried on the steam drier before seasoning in the humidity room.

DISCUSSION OF RESULTS

In the tables of tabulated data, values have been given for the air permeability, the oil permeability, and the ratio of these two values for the various samples studied. In calculating the value of the ratio, the highest observed value of the oil permeability has been used. It is to be noticed that in all cases, except for the most permeable samples, a pronounced decrease in the oil permeability occurred as successive measurements were made and oil was continuously forced through the sample. (It is, of course, necessary to release the pressure driving the oil through the sheet between successive measurements in order to replenish the oil in the capillary bulb from the oil supply.) In these cases, the first observed value of the oil permeability was invariably the highest one and was the one used in calculating the ratio of air to oil permeability.

As a result of the many observations made during the course of the investigation, it may be stated that the decrease in oil permeability, even in the case of those samples showing this effect in the most pronounced degree, occurs only when oil is flowing through the sheet. That is, when samples are removed from the instrument and allowed to stand for various lengths of time, no further decrease in oil permeability occurs.

Furthermore, in regard to this characteristic decrease in oil permeability as successive oil permeability measurements are made,

it has been impossible even in the long continued series of tests shown in Table IX to detect any leveling off of the value of the oil permeability which would lead one to believe that it was approaching a constant value.

The first oil permeability measurements were made with castor oil on three different commercial samples: (1) a mimeo sheet; (2) an inexpensive bond sheet, "White Valley Bond"; and (3) Whatman's filter paper no. 50. The data are shown in Tables I, II, and III. The important points here are that there is a definite relationship between oil and air permeability and that the oil permeability of the bond sheet decreases as oil is continuously forced through it. A possible explanation of this anomalous behavior is that oxidation of the castor oil was occurring and a film of oxidized and more viscous oil was being formed on the surface of the capillaries within the sheet, thus reducing the apparent permeability of the sheet. Accordingly, it was decided to change from castor oil and recalibrate the instrument on a mineral oil having greater stability towards oxidation. A heavy mineral oil, (Valveline SAE 50) was chosen.

With this mineral oil the permeability of the "White Valley Bond" and of the Whatman's filter paper no. 50 was again determined. The data are shown in Tables IV and V. The agreement of the values obtained with the mineral oil and with the castor oil is excellent, both for the oil permeability and for the ratio of air to oil permeability. The data shown in Table V(b) were obtained at the very low driving pressure of 0.137 lb./sq.in., which was secured by making use

of the pressure head of the column of oil alone (no external pressure applied from the nitrogen cylinder). No explanation can be offered for the rather high value found for the ratio of the air to oil permeability.

All subsequent measurements were made with Valvoline SAE 50, except as otherwise noted.

Before proceeding to the results secured from the measurements on handsheets it may be well to state briefly the possible explanations for the observed characteristic decrease in oil permeability as successive oil permeability measurements are made.

The Oxidation Theory: It is possible that the oil may be oxidized in flowing through the sheet and gradually build up a film which acts effectively to plug the sheet structure and lower the permeability.

The Fibril Breakage Theory: Within the fibrous structure of the sheet there are small fibrils which may project outward from the surface of the fibers into the capillary spaces between the fibers. It is conceivable that the flow of oil through the sheet could break off some of these fibrils and thereby plug the capillary openings, causing a reduction in permeability. This theory is supported by considerations of viscosity relationships. Viscosity is usually defined by the equation $\frac{F}{S} = \eta \frac{dv}{dx}$, where F is the force producing shear over the area S , η is the coefficient of viscosity of the liquid, and $\frac{dv}{dx}$ is the velocity gradient through the liquid. If this equation is applied to the case

of fluid flow through a small capillary we have $(\eta \frac{dv}{dx})/dx = (\eta R^2 P)/2\pi RL = RP/2L$, where R is the radius of the capillary, L is its length, and P is the pressure differential producing flow. Therefore, the shearing force exerted on unit area of the wall of the capillary or on unit area of a fibril projecting therefrom is $(\eta \frac{dv}{dx})/dR = RP/2L$. The shearing force for a given capillary within the sheet structure is thus proportional to the pressure causing fluid flow. In the case of the air permeability measurements this pressure is about 10 cm. of kerosene or 0.115 lb./sq.in. In the case of the oil permeability measurements, this pressure may be anywhere from 10 to 100 lb./sq.in. Consequently, the drag forces tending to break off any given fibril are roughly from 100 to 1000 times as great when oil permeability measurements are made as when air permeability measurements are made. If the breaking off of fibrils and consequent plugging of the sheet structure is actually the cause of the observed decrease in permeability, then this effect would be expected, in accordance with the above considerations, to be much more pronounced in the oil permeability measurements than in the air permeability measurements. This is in accordance with the experimental facts (no decrease in μ_A has been observed; the decrease in μ_o between successive measurements is considerable in many cases).

The Filtration Theory: Since the oil is a mixture of hydrocarbons of different molecular sizes, it is possible that some fraction might be filtered out by the sheet and thus plug the porous structure. This same reasoning would hold true if there were minute solid particles present in the oil.

The Streaming Potential Theory: If a potential difference between the upper and lower surfaces of the sheet is produced by the flow of oil, then this potential difference would tend to retard the rate of flow and thus cause a decrease in the permeability.

The data for Beater Run No. 1 have been shown in Table VI and require no comments; the physical data which further characterize these sheets are shown in Table XIX.

The air and oil permeability data for Beater Run No. 2 appear in Table VII, and the physical data are in Table XX. The following summary may aid at this point:

Sample identi- fication	$\mu_a \times 10^{13}$ sq. cm.	$\mu_o \times 10^{13}$ sq. cm.	μ_a/μ_o
L-5"	13380	9200	1.46
L-10"	1258	830	1.52
L-15"	220	138	1.59
L-20"	21.0	12.0	1.75
L-25"	4.81	1.86	2.58

The air permeability range observed in this group of samples is about 1 to 3000. From these data it is of course obvious that the samples may be ranked in the same order by the air permeability data as by the oil permeability data. From the oil permeability data of Table VII it may be concluded that, as the permeability of the sheet is reduced by beating, the characteristic drop in oil permeability between successive measurements becomes more and more pronounced. The values for the ratio of air permeability to oil permeability show that this ratio is not a true constant, but that it increases with decreasing

permeability. The rate of increase of this ratio also seems to increase rather sharply with decreasing permeability--viz., 1.59, 1.75, 2.58.

The effect of petroleum ether extraction on air and oil permeability measurements is shown in Table VIII. That petroleum ether extraction produced no appreciable change in the physical structure of the sample was shown by the fact that only a very slight change was produced in the air permeability when the sample was allowed to stand under petroleum ether for long periods of time. This sample showed a rather pronounced decrease in oil permeability as successive measurements were made. Washing with petroleum ether completely removed the oil from the sample and restored both its air and oil permeabilities almost exactly to their original values. The petroleum-ether-washed sheet exhibited, just as before, the characteristic decrease in oil permeability as successive measurements were made. These data do not support the previously proposed fibril breakage theory for, if the decrease in oil permeability is due to plugging of the sheet structure by fibrillar debris, it is difficult to understand how such debris could be completely washed out of the sheet structure by the rather gentle washings with petroleum ether. On the other hand, any or all of the other three theories might be supported by these results.

The data for the effect of reversal of direction of flow on oil permeability are shown in Table IX. For a sample which showed a pronounced decrease in oil permeability between successive measurements, the effect of inversion of the sheet so as to reverse the direction of flow was to cause the oil permeability to return almost,

but not quite, to its original value. These results do not support the streaming potential theory for, if a potential were built up across the sheet due to the flow of oil, it would be expected that this potential would aid the flow of oil immediately after inversion of the sample and thus cause the observed oil permeability to be higher than the original value--in fact, as much higher than the original value as the permeability just prior to inversion was lower than the original value. Nor do these results fall in line with the oxidation theory, for it is inconceivable that the reversal of the direction of flow could cause the almost complete removal of a film of oxidized and more viscous oil from the capillary openings. On the other hand, these data agree with what would be expected either from the fibril breakage theory or the filtration theory.

During the series of measurements shown in Table IX the refractive index of the oil was determined both before and after passage through the sheet. It was impossible to detect even the slightest change in the refractive index due to passage through the sheet. It was also impossible to detect any end value or leveling off of the characteristic decrease in oil permeability with successive measurements, even after the series of long-continued measurements on the same sample.

Without recalibration of the instrument, a mineral oil called "Bayoj", from which the unsaturates had been removed in the refining process, was substituted for Valvoline SAE 50. The viscosity of the oil was not determined, but it was very much less than that of

Valvoline SAE 50. Again, in these tests, the characteristic decrease in oil permeability with successive measurements was observed, although not for exactly the same samples nor in exactly the same degree as for Valvoline SAE 50. Since the "Baysj" is not easily oxidized, these results throw considerable doubt on the oxidation theory.

The results of Filler Run No. 1 appear in Table XI, and the physical data are in Table XXI. The following summary may be helpful:

Sample identi- fication	$\mu_a \times 10^{11}$ sq. cm.	$\mu_o \times 10^{11}$ sq. cm.	μ_a/μ_o
L-0%	2.03	1.24	1.63
L-5%	2.21	1.31	1.69
L-20%	3.62	2.28	1.59
L-80%	3.97	2.38	1.67
L-271%	5.99	3.21	1.86

The effect of clay filler is, thus to increase the permeability of the sheet, but large amounts of clay are required to produce a significant change. It is obvious that these samples may be ranked in exactly the same order by air permeability measurements as by oil permeability measurements. The values obtained for the ratio of air to oil permeability seem to be fairly constant, except for the most permeable sheet where the value is a bit high.

The air and oil permeability data for Sizing Run No. 1 appear in Table XII, and the physical data are in Table XXII. The following summary is of interest:

Sample identi- fication	$\mu_a \times 10^{11}$ sq. cm.	$\mu_o \times 10^{11}$ sq. cm.	μ_a/μ_o
L-0%	2.14	1.34	1.60
L-1%	2.40	1.56	1.54
L-2%	2.54	1.69	1.50
L-4%	3.55	2.31	1.54

The effect of rosin size, therefore, was to increase slightly both the air and oil permeabilities. The ratio of the air to oil permeability seems to be independent of the amount of rosin size in the sheet. These samples may be ranked in exactly the same order by air permeability measurements as by oil permeability measurements.

The air and oil permeability data for Beater Run No. 3 are shown in Table XIII, and the physical data are in Table XXIII. The following summary is helpful:

Sample identi- fication	$\mu_a \times 10^{11}$ sq. cm.	$\mu_o \times 10^{11}$ sq. cm.	$\frac{\mu_a}{\mu_o}$
L-2"	91.0	61.7	1.47
L-6"	45.2	31.0	1.46
L-11"	18.0	11.7	1.54
L-15"	9.66	5.84	1.65
L-20"	4.22	2.40	1.76

Here, the pulp was a hardwood bleached kraft. Again, the samples fall in exactly the same order by air permeability measurements as by oil permeability measurements. From the oil permeability data of Table XIII, it may be concluded that, as the permeability of the sheet is reduced by beating, the characteristic drop in oil permeability between successive measurements becomes more and more pronounced. The values for the ratio of air permeability to oil permeability show that this ratio is not a true constant, but that it increases with decreasing permeability.

The air and oil permeability data for Filler Run No. 2 are shown in Table XIV, and the physical data are in Table XXIV. The

following is a summary:

Sample identi- fication	$\mu_A \times 10^{12}$ sq. cm.	$\mu_D \times 10^{12}$ sq. cm.	μ_A/μ_D
L-0%	9.31	5.81	1.60
L-5%	10.8	7.22	1.50
L-20%	17.7	11.0	1.61
L-80%	47.3	29.4	1.61
L-312%	420.	259.	1.62

The filler was calcium carbonate, which, it may be seen, increases the permeability of the sheet to a much greater extent than does the clay of Filler Run No. 1. These sheets may be ranked in exactly the same order by air permeability measurements as by oil permeability measurements.

The data for the effect of antioxidant on oil permeability measurements have been shown in Table XV. In view of the results shown here and those of Table X the oxidation theory for the explanation of the characteristic decrease in oil permeability between successive measurements must be discarded entirely.

The air and oil permeability data for Sising Run No. 2 are shown in Table XVI, and the physical data are in Table XXV. The following summary is of interest:

Sample identi- fication	$\mu_A \times 10^{12}$ sq. cm.	$\mu_D \times 10^{12}$ sq. cm.	μ_A/μ_D
L-0%S	8.99	5.08	1.77
L-2%S	7.08	4.00	1.77
L-4%S	10.2	6.45	1.58
L-8%S	8.60	5.64	1.52
L-4%S 4%R	8.13	4.96	1.64

The data show no definite trend, so it is impossible to draw conclusions as to the effect of starch on air and oil permeability. The samples may be ranked in the same order by air permeability values as by oil permeability values with but one exception.

A study of the filtration effect has been made, using three sheets of "White Valley Bond". The data are shown in Table XVII. First, the air permeabilities of the three samples were measured. Then they were placed in series in the air permeability instrument with sample (a) on top, (b) in the middle, and (c) on the bottom. Oil permeability measurements were made until the permeability of the composite sample had decreased considerably. Then, the three sheets were taken out of the instrument and their oil permeabilities determined separately. The air to oil permeability ratios were calculated. These values were for (a) 1.79; (b) 1.72; (c) 1.63. The fact that the sheet on top showed the greatest value for this ratio indicates that its oil permeability had suffered the greatest decrease. This is in direct support of the filtration theory. That these three samples had originally the same values for the air to oil permeability ratios was shown by subsequently extracting them with petroleum ether to remove the oil and then redetermining this ratio.

The effect of distillation of the Valvoline SAE 50 on oil permeability measurements has been shown by the data in Table XVIII. The distilled oil had a considerably lower viscosity than the original, but its viscosity was not determined. Permeability measurements made with this oil showed the characteristic decrease between successive

measurements, but not to the same degree as did the measurements previously made with the original oil on a similar sample (Table VII (f)).

CONCLUSIONS

Of the many handsheets tested in this work and which represent the effect of type of pulp, degree of beating, type and amount of filler, and type and degree of sizing, all (with but a single exception) may be ranked within their individual groups in exactly the same order by air as by oil permeability measurements.

The oil permeability measurements have brought to light the fact that most sheets of paper exhibit the phenomenon of decreasing permeability as oil is continuously forced to flow through any one sample. This characteristic decrease in oil permeability as successive measurements are made is barely detectable, if present at all, in the most permeable samples, but it becomes more and more pronounced as the permeability of the sample is decreased. Furthermore, this effect is connected in some manner with the viscosity of the fluid, for in those cases in which oils of lower viscosity ("Bayol" and distilled Valvoline SAE 50) were used, the same degree of decrease in oil permeability with successive measurements could be observed only for samples of relatively much lower permeability.

The air permeability of paper is a true constant, exhibiting no change as air is continuously sucked through a given sample.

The ratio of air permeability to oil permeability is not a true constant, but for most of the sheets examined its value lay between 1.4 and 1.7. The data for Beater Runs No. 2 and No. 3 are the principle

exceptions to this generalization. Here, the ratio of air to oil permeability increases with decreasing permeability, and rather sharply so for the samples of least permeability.

The only data to be found in the literature for permeability measurements on the same sample with both liquids and gases are those given by Muskat (41). These results show excellent agreement between permeabilities obtained from liquid flow and from air flow measurements on sandstones. The permeability range was around 1.5×10^{-6} sq. cm., or about a thousand times that of the most permeable sheets investigated in this work. The samples tested in this investigation lie in a permeability range which has been heretofore almost entirely unexplored by liquid flow measurements.

It is entirely possible that the oils used in this work for permeability measurements might have a molecular structure consisting not of single molecules alone but also of groups of associated molecules. In making viscosity measurements by ordinary means, such as the falling ball method, it is likely that none of these associated molecules are broken down and that the coefficient of viscosity thus determined has to do only with shear between molecular groups. When such an oil is used for permeability measurements on paper, it is probable that some of the molecular groups may be too large to pass unchanged through the pores of the sheet. These molecular groups must first be broken down into smaller units and work would be required to accomplish this. The energy lost in breaking down these molecular units would make the viscosity of the oil under these conditions higher than the viscosity

obtained by ordinary methods and would cause the apparent permeability of the sample to be lower than its true permeability, leading to a value greater than one for the air to oil permeability ratio as actually was found to be the case. Furthermore, when the permeability of the sheet is reduced enormously by beating, as in the actual experiments, the ratio of the number of very small pores to the number of larger pores present in the sheet structure must increase considerably. In such a sheet a greater energy loss would occur, resulting in an even lower value of the apparent oil permeability and a correspondingly higher value of the air to oil permeability ratio. The experimental results are in accordance with such a line of reasoning.

The lack of scientific knowledge regarding the molecular structure of liquids and the fundamental concepts of liquid viscosity is truly startling. To quote from a well known work (43): "— it may be said that many arguments have been brought together to support the view that regional structures of a temporary character are present in liquids and that these groups possess a certain rigidity, which, however, is constantly counteracted by the 'melting down' of the groups. The problem, however, of what actually happens in these groups during a process of shearing motion still remains somewhat vague: we may either assume, with Andrade, that the primary effect is the transfer of momentum at 'favourable' collisions, or we may suppose that the shearing stress produces an elastic deformation of the groups, which is counteracted by a relaxation phenomenon, connected with the decay and growth of the groups. Which of the two processes is the more

important may depend upon the nature of the liquid."

The present investigation has served merely to break the ground in the very fertile and relatively virgin field of liquid permeability measurements on media of low permeability. It is entirely possible that further investigation of liquid permeability measurements on such media as the lowly sheet of paper might serve to clarify the present conception of the molecular structure of liquids.

Mention has not previously been made of the interesting phenomenon known as "slippage". That slippage may occur when gases flow through capillaries is a well-known fact, particularly when the radius of the capillary is of the order of magnitude of the mean free path of the gas molecules. Carson (7) found that a decrease in the total pressure at which air permeability measurements were made caused an increase in the rate of air flow through the paper due to slippage. In a later work (8) he made use of this phenomenon to determine pore sizes in his samples.

SUMMARY

An instrument has been designed, constructed, and calibrated which is capable of measuring the oil permeability of paper over a wide range of permeabilities.

An air permeability instrument similar to that of Carson (6) has been constructed and calibrated by a procedure which eliminates an error that Carson allowed to enter his work.

These two instruments were used to study the air and oil permeabilities of identical areas of various papers.

The Darcy equation has been used for calculating the permeability values in fundamental C. G. S. units.

The samples tested included various commercial papers as well as a wide range of types of handsheets.

The effect of the following variables on air and oil permeability measurements was determined: type of pulp, degree of beating, type and amount of filler, and type and degree of sizing. Beating decreases both the air and oil permeability. Both clay and calcium carbonate fillers increase both the air and oil permeability. Rosin size also increases both the air and oil permeability. Starch size produced no observable trend.

Permeability measurements with several different oils on

the same paper gave concordant values of the oil permeability.

Of the many handsheets tested, all, with but a single exception, may be ranked within their individual groups in exactly the same order by air as well as by oil permeability measurements.

The oil permeability measurements have brought to light the fact that most sheets of paper exhibit the phenomenon of decreasing permeability as oil is continuously forced to flow through any one sample. This characteristic decrease in oil permeability as successive measurements are made becomes more and more pronounced as the permeability of the sample is decreased.

The air permeability of paper is a true constant, exhibiting no change as air is continuously sucked through a given sample.

The ratio of air permeability to oil permeability is not a true constant, but for most of the sheets examined its value lay between 1.4 and 1.7.

REFERENCES CITED

1. Institute of Paper Chemistry, Paper Trade J. 105, no. 8:39-42 (Aug. 19, 1937).
2. Institute of Paper Chemistry, Paper Trade J. 107, no. 18:56-58 (Nov. 3, 1938).
3. Vincent, Howard L., Paper Trade J. 110, no. 22:29-33 (May 30, 1940); Tech. Assoc. Papers 23:187-191 (1940).
4. Institute of Paper Chemistry, Paper Trade J. 105, no. 26:35-42 (Dec. 23, 1937).
5. Shaw, Merle B., and Simmons, Robert H., J. Research Natl. Bur. Standards 22:285-289 (1939).
6. Carson, Frederick T., J. Research Natl. Bur. Standards 12:567-585 (1934).
7. Carson, Frederick T., J. Research Natl. Bur. Standards 12:587-608 (1934).
8. Carson, Frederick T., J. Research Natl. Bur. Standards 24:435-442 (1940).
9. Lochmann, G., Angew. Chem. 53:505-508 (1940).
10. Institute of Paper Chemistry, Paper Trade J. 110, no. 4:44-50 (Jan. 25, 1940).
11. Sullivan, R. R., and Hertel, K. L., J. Applied Physics 11:761-765 (1940).
12. Peek, R. L., Jr., and McLean, D. A., Ind. Eng. Chem., Anal. Ed. 6:85-90 (1934).
13. Washburn, Edward W., Phys. Rev. 17:273-283 (1921); quoted by (10). p. 46.
14. Larocque, G. L., Pulp Paper Mag. Can. 39:99-105, 123 (1938).
15. Prior, P. H. Experiments in printing. Am. Newspaper Publ. Assoc., Mechanical Bull. 156:8-24 (Jan. 25, 1937).
16. Fairbrother, J. A. V., and Crenney, R. G. W., Patra J. 1, no. 3:106-113 (1937-1938).
- 16a. Weymouth, F. A., Paper Trade J. 114, no. 15:37-40 (April 9, 1942).
17. Larocque, G. L., Pulp Paper Mag. Can. 39:106-119 (1938).

18. Ant-Wuorinen, Ollie, and Backman, Albert, Finnish Paper Timber J. 20:222-226, 228, 230, 232, 234-236, 238-240, 242-243(1938).
19. Larocque, G. L., Pulp Paper Mag. Can. 38:77-84(1937).
20. Foote, James E., Paper Trade J. 109, no. 14:40-48(Oct. 5, 1939); Tech. Assoc. Papers 23:558-566(1940).
21. Patra J. 1, no. 6:230-235(1937-1938).
22. Institute of Paper Chemistry, Paper Trade J. 109, no. 15:19-24, 26(Oct. 12, 1939).
23. Ezy, L., Pulp Paper Mag. Can. 38:499-501(1937).
24. Abrams, Allen, Paper Trade J. 84, no. 3:44-47(Jan. 20, 1927).
25. Albert, Gerard A., Paper Trade J. 101, no. 11:31-35(Sept. 12, 1935).
26. Albert, Gerard A., Paper Trade J. 106, no. 15:30-32(April 14, 1938).
27. Bekk, Julius, Zellstoff u. Papier 18:698-700(1938).
28. Hammond, Joseph, Paper Trade J. 103, no. 21:37-39(Nov. 19, 1936).
29. Goldberg, Alan A., J. Soc. Chem. Ind. 56:249T-252(1937).
30. Lhomme et Argy, and Baird, P., Papeterie 53:1438, 1441-1442, 1445 (1931); Pulp Paper Can. 33:177-179(1932).
31. Emannelli, L., Paper Trade J. 83, no. 10:48-50(Sept. 8, 1927); Tech. Assoc. Papers 11:71-73(1928).
32. Doughty, R. H., Seborg, C. O., and Baird, P. K., Paper Trade J. 94, no. 22:31-33(June 16, 1932); Tech. Assoc. Papers 15:287-289 (1932).
33. Herzberg, W., Wochbl. Papierfabr. 46:1977-1979(1915).
34. Edwards, R. S., J. Intern. Soc. Leather Trades' Chem. 16:439(1932).
35. Simmonds, F. A., Paper Trade J. 97, no. 10:40-42(Sept. 7, 1933); Tech. Assoc. Papers 17:401-403(1934).
36. Friess, Herbert, Gasmasken 10:29-34(1938).
37. MacGee, A. Ernest, J. Am. Ceram. Soc. 9:814-822(1926).
38. Stull, Ray T., and Johnson, Paul V., J. Research Natl. Bur. Standards 25:711-730(1940).

39. Washburn, Edward W., and Bunting, Elmer N., J. Am. Ceram. Soc. 5:112-130(1922).
40. Benton, A. F., J. Ind. Eng. Chem. 11:623-629(1919).
41. Muskat, M. The flow of homogeneous fluids through porous media. 1st ed., especially p. 76-79. New York, McGraw-Hill, 1937. 763 p.
42. Institute of Paper Chemistry, Paper Trade J. 109, no. 13:18-20, 22(Sept. 28, 1939).
43. Burgers, J. M. Mechanical considerations---Model systems---Phenomenological theories of relaxation and of viscosity. In First report on viscosity and plasticity. Especially p. 72. Amsterdam, Noord-Hollandische Uitgevers-Maatschappij 1935.