EFFECTS OF SIZE AND SHAPE OF SPECIMENS AND GAS SLIPPAGE PHENOMENA IN THE MEASUREMENT OF COAL PERMEABILITY TO GAS FLOW

by

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Thesis submitted to the Graduate Faculty of the
Virginia Polytechnic Institute
in candidacy for the degree of
MASTER OF SCIENCE
in
Mining Engineering

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I. INTRODUCTION

A. Statement of Problem

The permeability of coal to gas flow is one of the fundamental factors affecting the explosive-gas or firedamp emission in coal mines. The emission of firedamp from coal seams during the extraction process represents one of the main hazards in coal mining and it has been the subject of much study and investigation. Interest in degasification of coal seams prior to and during mining has grown and for degasification the knowledge of coal permeability becomes paramount. Coal is a heterogeneous type of rock and has a low value of permeability. Its permeability is highly variable since it is dependent upon many factors such as the inherent structure and composition of the coal. The permeability of a given specimen is also affected by the number of fractures contained within the sample, and hence different geometries of coal specimens to be tested can be expected to give different values of permeability. It can be understood that predictions of coal-seam gas emission, based on tests of small samples, can be misleading due to the problem of obtaining representative test specimens.

The properties of the fluid used for the permeability measurement introduce additional factors to be considered which may affect the permeability of the coal. It is known that for low permeability measurements using gas flow, a phenomenon called the Klinkenberg effect or gas slippage may occur. The theory of gas slippage as applied to the measurement of the permeability of a porous medium to gas has been so well substantiated in recent years that any measurement to determine this permeability by using gas at low pressures, of two atmospheres or less, should be taken into consideration and be corrected for.[1,2,3,4]

B. Approach to the Problem

The study of coal permeability and the laboratory tests were based on the literature and practice of the permeability measurement of reservoir rocks as applied in the petroleum industry. The general method by which permeability was determined has been standardized by the American Petroleum Institute in a code procedure.[5] Permeability of a medium can be calculated by the use of D'Arcy's law by measuring the rate of flow of a fluid of known viscosity through a medium of well-defined geometry under a measured pressure differential. It is a common practice in the oil industry to determine the permeability of core material with dry air by using the apparatus arranged to operate with the outlet of the sample at or near atmospheric pressure. Some studies on coal permeability have been made in the mining engineering laboratories at Virginia Polytechnic Institute. Using dry air as the fluid, tests have obtained the permeability of one inch cubes of selected coals and have provided information on the effects of the size factor in the permeability values obtained.[6,7,8,9]

C. Purpose of Study

The work reported herein, which was based on previous investigations and literature review, was undertaken in an effort to develop a simple apparatus and method for the determination of permeability measurements on coal samples. It was the purpose of this study to investigate the flow of gas through coal as follows:

1. To investigate the effects of specimen size on the permeability measurements of gas flow in coal samples, and to find a standard size of coal sample for permeability measurement.
2. To investigate the effects of gas slippage.
3. To correlate the permeability values of core-samples versus cube-samples.

II. THE REVIEW OF LITERATURE

A. Nature and Origin of Firedamp

Firedamp is a term which is commonly applied to a mixture of explosive gases. However, it is convenient to extend its usage to include all gases given off from coal seams and associated carboniferous strata. The major combustible constituent is methane which is usually present in the range of 80 to 90 per cent by volume. Other gases found in firedamp are the higher hydrocarbons such as ethane, propane, and butane together with varying amounts of carbon dioxide, nitrogen and helium.[10] At shallow depths, the proportion of methane declines with the firedamp reverting to nitrogen and carbon dioxide.[11]

In considering the origin and nature of firedamp associated with coal measures, it is generally accepted that the history of these gases is the same as that of the coal.[12] Coal was formed by a complicated chemical reaction process from plant material, and it was during this process that the firedamp contained in the coal was formed. The composition and properties of the organic substances of the coal underwent changes, and gaseous substances were gradually discharged. This discharge was one of the main specific properties of the metamorphic process that occurred from the lignite to graphite stage. During the formation of ordinary coal of an average degree of metamorphism, approximately 25 per cent of the total organic mass is converted into methane. In the further conversion of coal into anthracite, another 10 per cent of its total mass is transferred to the gas phase.[13] The gases evolved may accumulate in a disorbed state within the pores and fractures of the coal and associated strata.

Coal in an undisturbed seam may contain large amounts of firedamp at high pressure. The quantity of methane which saturates many coal seams in their present condition is so great that the coal deposits can be considered as methane-coal deposits.[13] The ability of coal to store large amounts of firedamp is due to the micro-porous structure which presents a large internal surface on which the gas is physically absorbed to form a very thin layer. The formation of the absorbed layer may be likened to the condensation of a vapor to form a film of liquid. Reduction of gas pressure such as occurs when the coal is worked at the coal face causes desorption to take place which may be likened to the evaporation of the condensed layer.[10] Fracturing or breakage of the coal immediately reduces the pressure of the gas on the newly exposed surface and desorption occurs almost instantaneously at the surface of the break. Hinsley [10] concluded from his experiments that firedamp emitted from the coal seam will enter the mine ventilation system from the following sources: the coal face, the coal broken by the mining processes, the roof, floor and the waste. The gas from the coal face will depend on the gas pressure in the coal ahead of the coal face and the degree of development of cracks and breaks caused by roof and floor pressure. The emission from the coal broken by the machine will depend on the degree of degradation, the permeability of the coal and the original gas pressure. The amount of gas coming from the roof, floor and the waste will depend on the presence of roof coal, the proximity of other seams above and below the seam being worked, permeability of the strata and the amount of breakage induced in the strata.

B. Porous Media and Permeability

The flow of fluids through porous materials is a subject of importance in many fields of engineering. Such diverse fields as petroleum engineering, soil mechanics, ground water hydrology, and sanitary engineering require understanding of such flow phenomena. It is also becoming more important to the study of the gas emission in coal mines and the efforts for the degasification of coal seams. The permeation of coal by pores and cracks also affects the measurement of elastic moduli inasmuch as they reduce the amount of load bearing substance.[14]

To study the flow of fluid through porous media, it is necessary to clarify the definition of porous media. Porous media are defined as solid bodies containing pores. Pores are void spaces distributed through the material which is to be called porous. Extremely small voids are called molecular interstices and very large ones are called caverns. Those spaces which are intermediate in size between molecular interstices and caverns are termed pores.[15] The pores in a porous system may be interconnected or non-interconnected. The interconnected part of the pore system is called the effective pore space of the porous medium.[15]

Permeability of rock may be defined as its fluid conductivity. This means the ability of a fluid to flow through the interconnected pore network of a porous medium. Fulton [2] differentiated three kinds of permeability:

Specific permeability may be defined as the ability of a porous medium to conduct fluid when the saturation of that fluid in the material is 100 per cent.

Effective permeability of a porous material is the ability of that material to conduct a fluid when the saturation of that fluid in the material is less than 100 per cent of the pore space.

Relative permeability is defined as the ratio of the effective permeability to a given fluid at a definite saturation to the permeability at 100 per cent saturation.

The permeability of coal is based on fractures connecting the pore space left as the result of some degree of devolatilization or other changes of the substance from which coal was formed. Also contributing to the permeability of coal are fractures of two genetic types occurring in coal, the endogenetic and the exogenetic.[16] The endogenetic fractures owe their formation to the nature of the coal and are connected with the changes the coal undergoes during the coalification process. The exogenetic fractures appear in the coal due to the effect of external forces which occurred during the last stage of development by the folding of coal measures strata.

Indications have been found that the permeability of certain ranks of bituminous coal to gases tends to increase with the decrease in volatile matter up to a certain point. This phenomena indicates that the openings or pores were produced due to the squeezing out of volatile matter.[7] A study by Ammosov and Eremin [16] also came to the conclusion that the frequency and degree of development of the endogenetic fractures is closely connected with the metamorphic grade from lignite up to anthracite and the petrographic composition of the coal. The frequency of the endogenetic fractures varies along a curve with a maximum in the region of coal of the intermediate metamorphic grades (Figure 1). It is very important therefore to establish the interrelations between the petrographic peculiarities of the coal varieties and their gas permeability.

C. D'Arcy's Law

The knowledge of flow of fluids through porous material is of practical importance. An understanding of the mechanism of the flow involved obviously is a practical aid in the solution of many of the problems connected with the migration of fluid through porous material. A parameter, permeability, characterizing the fluid conductivity of a

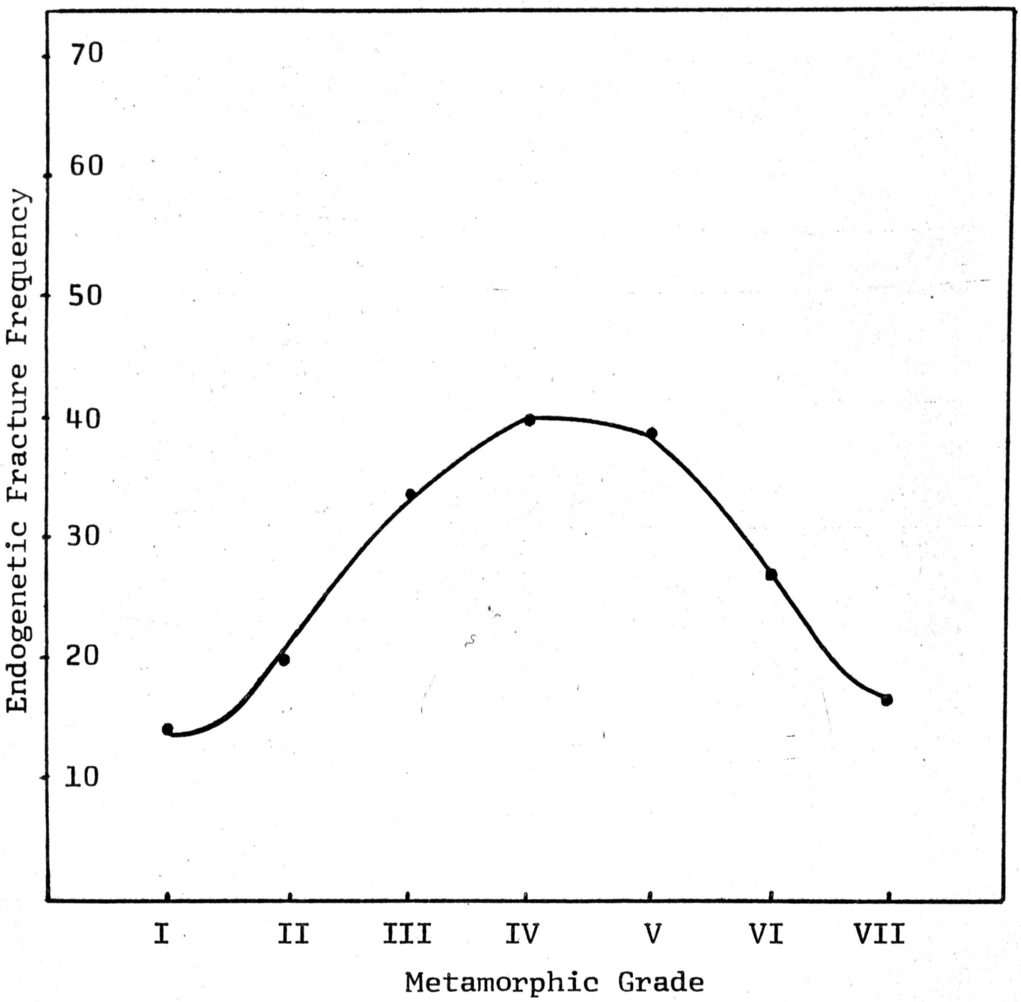

Figure 1. Changes in the Frequency of the Endogenetic Fractures with the Metamorphic Grade of the Coal.
(after Ammosov and Eremin[16])

porous material was meaningfully defined and first demonstrated by a French hydrologist, H. D'Arcy in 1856. The equation which defines permeability in terms of measurable quantities is called D'Arcy's Law. He was concerned with the problem of the flow of water through filter beds, which he found was directly proportional to its cross-sectional area and to the driving head, and inversely proportional to the length of flow through the filter bed:

$$Q = \frac{-K A (h_2 - h_1)}{L}$$

where: Q is the rate of flow,

A is the cross section of the filter bed,

L is the thickness of, or length of flow through the filter bed,

K is a constant depending on the properties of of the porous medium,

h_2-h_1 is the head of water inducing the flow.

The minus sign in the expression for Q indicates that the flow is in the direction opposite to the increasing head. Upon introduction of a new constant k, where $k = K U$, and k is the permeability of the medium while U is the viscosity of the fluid, D'Arcy's equation can take the form:

$$k = \frac{U\ Q\ L}{A\ (P_1 - P_2)}$$

where P_1 and P_2 are terminal pressures across the core.

To make specific use of the permeability concept as defined by D'Arcy's Law, it is necessary to define the unit by which the magnitude of the permeability may be expressed. Wyckoff, et al [17], introduced the unit used for permeability constant which is called the darcy. The permeability of a porous medium is one darcy if through it will flow one cubic centimeter per second per square centimeter of cross section of a fluid of one centipoise viscosity under the action of one atmosphere per centimeter pressure gradient.[18]

Thus $$1 \text{ darcy} = \frac{1\ (\text{cm}^3/\text{sec}) \times 1\ (\text{cp})}{1\ (\text{cm}^2) \times 1\ (\text{atm/cm})}$$

The law as stated in the form given above involves some limitations in practice.[15] These limitations are:

1. The flow should consist of an inert homogeneous gas.
2. The flow should not be at high flow rates, since for high rates the laminar flow regime will breakdown and there will be turbulent flow.
3. The possible existence of a molecular effect which leads to the gas slippage phenomenon or Klinkenberg effect should be checked.

D. Gas Slippage Phenomena

The definition of permeability does not specify the fluid that should be used for permeability determinations. Air is commonly used as the fluid medium in gas permeability tests. The equipment usually employed for this determination is arranged to operate with the outlet of the sample at or near atmospheric pressure.[5] This practice is based on the fundamental assumption that, as long as the rate of flow is proportional to the pressure gradient, the permeability constant of a porous medium is independent of the fluid used in its determination. However, Muskat [19] found large discrepancies between the permeability of air compared to that of water. Most values found for water have been lower than for air. In this regard, Klinkenberg [3] proved that the discrepancies between air permeability and liquid permeability are due not to the unusual behavior of the liquids but to the unusual behavior of the gases. In the case of gases, the flowing fluid does not stick to the walls of the pores as required in D'Arcy's Law, and a phenomenon termed gas slippage or the Klinkenberg effect occurs. The validity of the theory of gas slippage as it is applied to the flow of gas through porous media has been well established.[1,2,3,4]

Fulton [2] explained the gas slippage phenomenon as follows. In the viscous flow of liquids and gases at high pressures through a capillary, the velocity of a thin layer of fluid adjacent to the walls of the capillary theoretically is zero. However, in gaseous flow when the ratio of the radius of the capillary to the mean free path of the gas is such that the intermolecular collisions decrease in importance, then collisions of the molecules with the walls of the capillary gain in importance. The gas seems to lose its grip on the solid surface of the capillary and the layer of gas next to the wall has a finite velocity.

Klinkenberg [3] has proved in his experiments that the observed permeability to gas is a function of the reciprocal mean pressure. The observed permeability to gas approaches a limiting value at infinite mean pressure which can be identified with the liquid permeability.

The Klinkenberg equation states:

$$k_a = k_L \left(1 + \frac{4 \, c \, \gamma}{r} \right)$$

where: k_a is the measured or apparent permeability of a porous sample, computed by D'Arcy's equation,

k_L is the true or liquid permeability,

r is the average radius of the capillaries,

c is a proportionality factor with an apparent value of slightly less than unity,[4]

y is the mean free path of gas molecule.

The meaning of the mean free path (y) can be clarified as follows:

> The path of a gas molecule at a given pressure must be an irregular zigzag having at each corner a collision with another molecule and consisting of a straight free path between collisions. The individual lengths of these free paths will vary widely. The average of their lengths will have a definite value which is called the mean free path at that pressure.[2]

Since the mean free path (y) is inversely proportional to the pressure, Klinkenberg states further that:

$$k_a = k_L \left(1 + \frac{b}{P} \right)$$

where $b = \frac{4\,c}{r}$ and P is the mean pressure in the system. It can be seen that the slipping of the fluid along the pore walls gives rise to an apparent dependence of permeability on pressure.

Gas slippage decreases as the mean free path of the molecules decreases. Since the mean free path of any gas decreases with increasing density, increase in static pressure results in lower apparent gas permeabilities. The effect of gas slippage can be corrected by making the permeability observations and calculations for each sample at several mean pressures and by plotting the values of the observed permeabilities against $\frac{1}{P}$.

E. Permeability Measurement

The measurement of the permeability of a sample essentially involves only a proper mounting of the sample whose dimensions are known with the provision for determining the pressure differential across the sample and the rate of flow of the fluid through it. In principle the measurement may be made either with liquids or gases and the sample can be either a cylindrical or rectangular form. Klinkenberg has shown that permeabilities, as ordinarily measured using air, varied depending upon the mean pressure used in the measurement. This variation is more striking for low permeability samples and decreases with increasing permeability.

Each measurement under a certain mean pressure will give the observed or apparent permeability value (k_a) of the sample. To find the true permeability value (k_L), related to the observed permeability as stated by formula: $k_a = k_L\ (1 + \frac{b}{P})$, measurements were made at several mean pressures and each k_a was then plotted against its reciprocal mean pressure. The slope of the line determines the value of b and the intercept on the k_a axis determines the value of k_L (see Figure 9).

The values of k_L and b can be solved for statistically by using the Least Squares Method. This solution was made possible by the fact that gas permeability is a linear function of the reciprocal mean pressure.[3] In this investigation the values of k_a , k_L , and b were determined by the use of a digital computer.

III. EXPERIMENTAL PROCEDURE

A. Instrumentation

To obtain accurate reproducible results of coal permeability measurements using air as the fluid, instrumentation was arranged as shown in Figures 2 and 3. It was designed to provide the following conditions:

1. Means to provide a supply of dry air, including the controlling devices to allow the air to pass through the coal sample under a certain desired pressure.
2. A unit of instruments for determining the pressure differential across the sample and the rate of flow of the fluid through it, as well as for measuring the temperature of the flowing air.
3. A device for holding the sample to be tested.

Other essential accessories include:

4. A device for measuring the linear dimensions of the sample.
5. A device for measuring time.
6. A device for measuring the very low permeability samples bu using a water displacement method.
7. A barometer to check the change in atmospheric

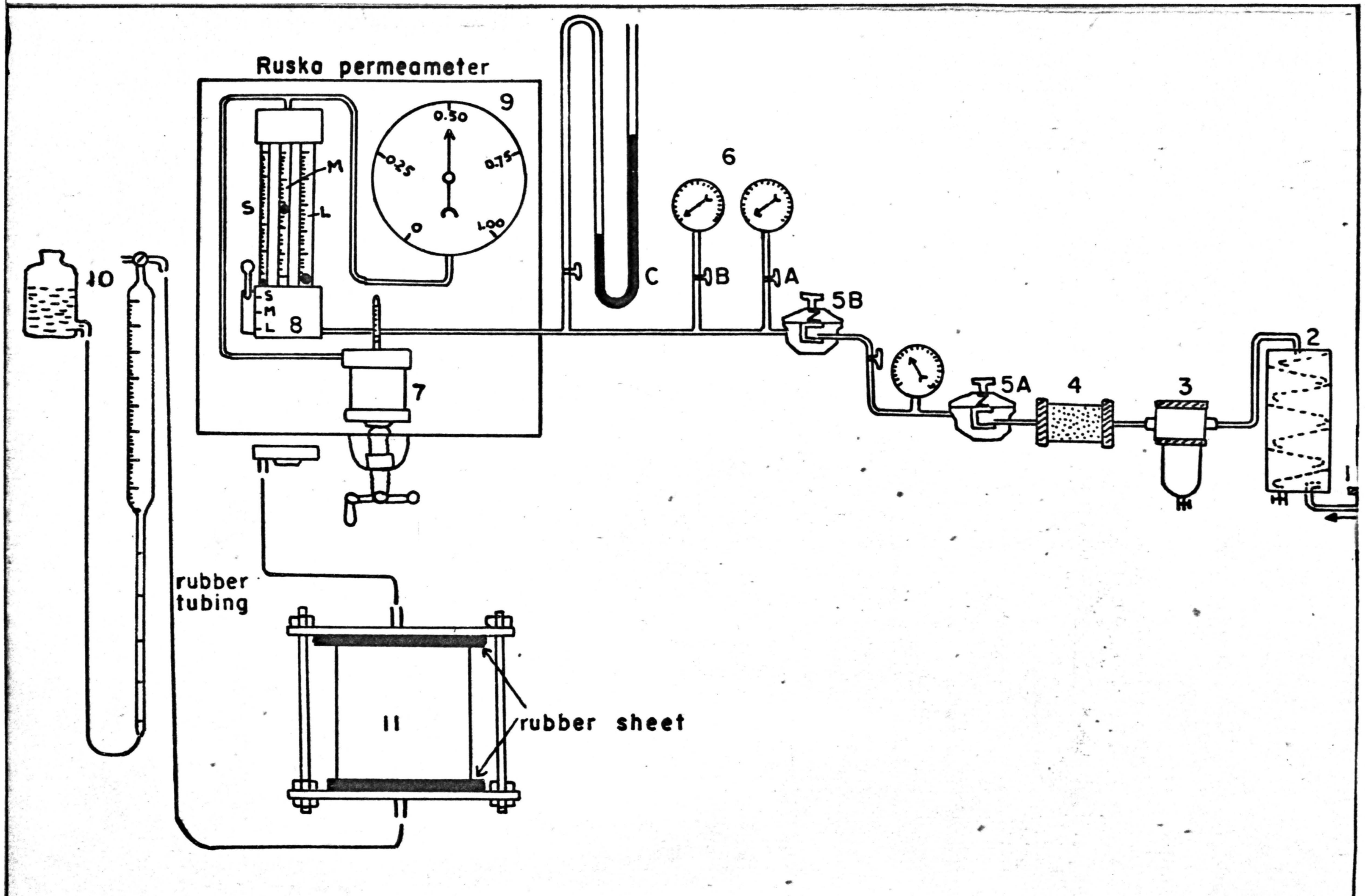

Fig. 2. Diagram Showing the Apparatus Used for Coal Permeability Measurement

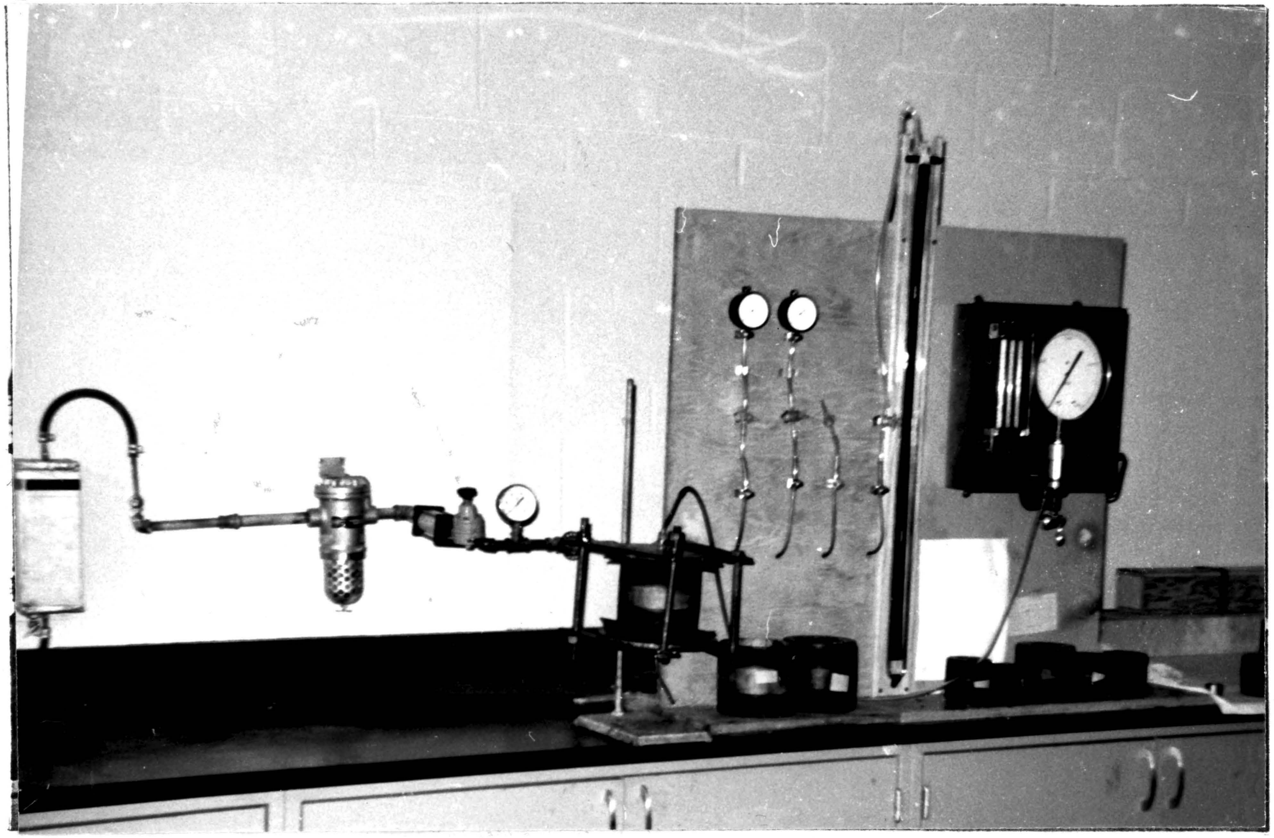

Fig. 3. Apparatus Used for Coal Permeability Measurement

pressure during measurement.

8. Provision for the airtightness of all connections in the air line.

Dry Air Supply

The existence of a compressed air line in the laboratory provided a convenient supply of air for the experiment. The air had to be first cleaned and dried. As is illustrated in Figure 2, compressed air from the main air line passed through a stopcock (1), entered a moisture-trap *) (2) and thence into a compressed air filter (3) which removed dirt, water and oil particles. The clean air then passed through an air-line moisture indicator (4). The clean dry air was then regulated by a valve regulator (5A) to produce a constant flow under a certain pressure, and was ready to be used for the test.

Pressure and Flowrate Reading

The instruments used were combined into a compact unitized piece of apparatus which is called a permeameter, the Ruska 1011 Permeameter being used in this experiment. A manifold with manometers of different ranges of pressure

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*) Moisture-trap was designed by Mr. R. I. Dillon, Industrial Engineering Dept., Virginia Polytechnic Institute.

reading were additionally installed: 0 - 60 mm Hg pressure gage (6A), 0 - 300 mm Hg pressure gage (6B) and 0 - 760 mm Hg U-tube mercury manometer (6C). The installation of the U-tube manometer insured correct readings of the pressure across the sample, as well as giving information for the corrections to be made to the Bourdon pressure gage reading of the permeameter due to changes in barometric pressure. The use of this manifold was indicated by the Recommended Practice of the American Petroleum Institute,[5] Item 57f which states that "the equipment must adequately provide for the measurement of pressures by liquid manometers or devices of equivalent accuracy, i.e. deadweight testers. In no case is the usual Bourdon gage to be relied upon for these measurements if reproducible results are desired."

The permeameter consisted of a core-holder with a built-in thermometer (7), triple range flowmeter with a selector valve (8), hand-calibrated Bourdon tube pressure gage (9), pressure regulator (5B) with a gas inlet connection, all of which were permanently interconnected and mounted on a panel with frame. The permeameter was calibrated to give the gas flow, $\overline{Q}$, in cubic centimeters per second at mean pressure (Figure 7). The upstream pressures at which the three tubes were calibrated had been selected so as to avoid turbulence in the samples.[20] The permeameter was calibrated by Ruska to operate at an upstream gage pressure of one atmosphere for the small tube (8S), 0.50 atmosphere for the medium tube (8M), and 0.25 atmosphere for the large tube (8L). An auxiliary installation of pipette (10) was provided to measure very low flow rates if readings could not be obtained from the flowmeter tubes.

Sample Holder

The core holder which is part of the Ruska Permeameter unit can only be used for small samples, one inch or smaller. To handle bigger samples, an auxiliary sample holder was used to mount the sample (11). It consisted of a steel sleeve, a top plate with an input tube, a bottom plate with an exhaust tube and clamp (Figure 4). The sample holder was designed so that all flow was through the sample. Care was taken that no air bypassed the sample through an imperfect seal between the sample and the walls of the metal sleeve of the sample holder.

B. Sample Preparation

The gross sample of coal for the experiment was obtained from Itmann No. 3 Mine. Description of the coal

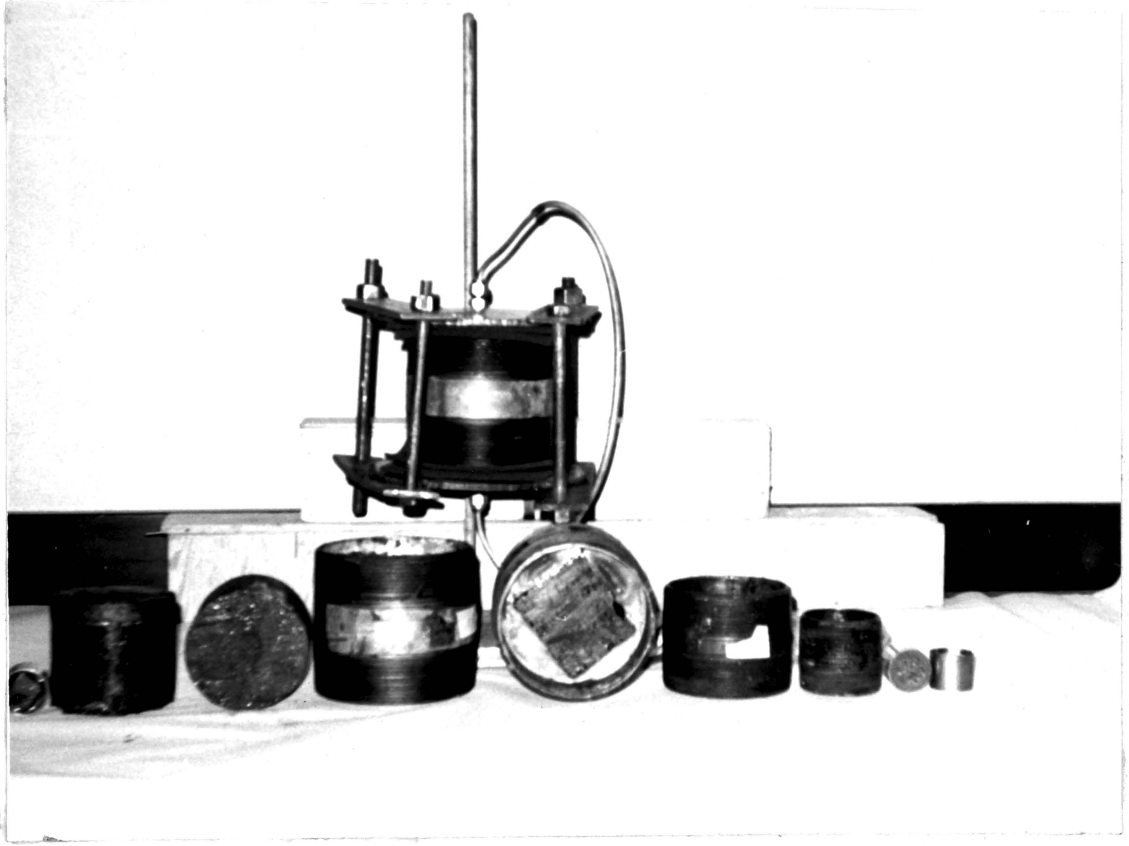

Fig. 4. Auxiliary Sample Holder

sample was given in Appendix B. The sample was first cut into desired sizes and shapes of specimens by use of either a masonry saw or a coring device. When each specimen had been finished to the desired final size by sanding and/or polishing, it was further treated by painting the sides of the specimen which were to be parallel to the direction of the gas flow. Each specimen was then mounted in the appropriate sample holder for its permeability measurement.

Cutting and Sizing the Coal Sample

A masonry saw, with a diamond impregnated blade (the Clipper Masonry Saw) shown in Figure 5, was used to cut and size the coal cube specimens with edge dimensions of one inch, two inches, three inches, and four inches. Cylindrical core specimens having diameters of one inch, two inches, and four inches were prepared with a Buffalo No. 21 drill press using thin-wall diamond impregnated coring bits (Steelset, Diamond Products, Fish-Schurman Corporation) which were water lubricated (Figure 6). The length of the core sample was made equal to the diameter. Due to the large size of the gross coal sample obtained from the mine, the coal was first cut by using a two-man cross-cut saw into sizes which could be handled by the diamond saw. Each specimen was polished with sandpaper to get smooth and even surfaces and then dusted with a dry air blast or brushed to remove loose particles adhering to the sample. Dimensions of the specimen were measured accurately with a micrometer, as any inaccuracy introduced errors.

Specimen Mounting

Each sample was mounted in a metal sleeve with an impermeable material so that air would flow only through the sample, parallel to the bedding plane. Care was taken to insure that the sample was perfectly sealed with the walls of the sleeve. Prior to mounting the specimen in the sleeve, the sides of the specimen facing the walls of the sleeve were painted with a quick drying paint (Varnish Products P3707) to avoid the penetration of the sealing material into the sample, as well as to seal off the sides from any possible leakage. For the one-inch samples, the metal sleeve was then pushed into a rubber sleeve of the corresponding size, which in turn was inserted into the sample holder sleeve (8), shown in Figure 2, and tightened with a screw to the permeameter unit. For larger samples, a steel sleeve with the mounted sample in it was placed between the top and bottom plates of the auxiliary sample holder (11)

Fig. 5. Clipper Masonry Saw

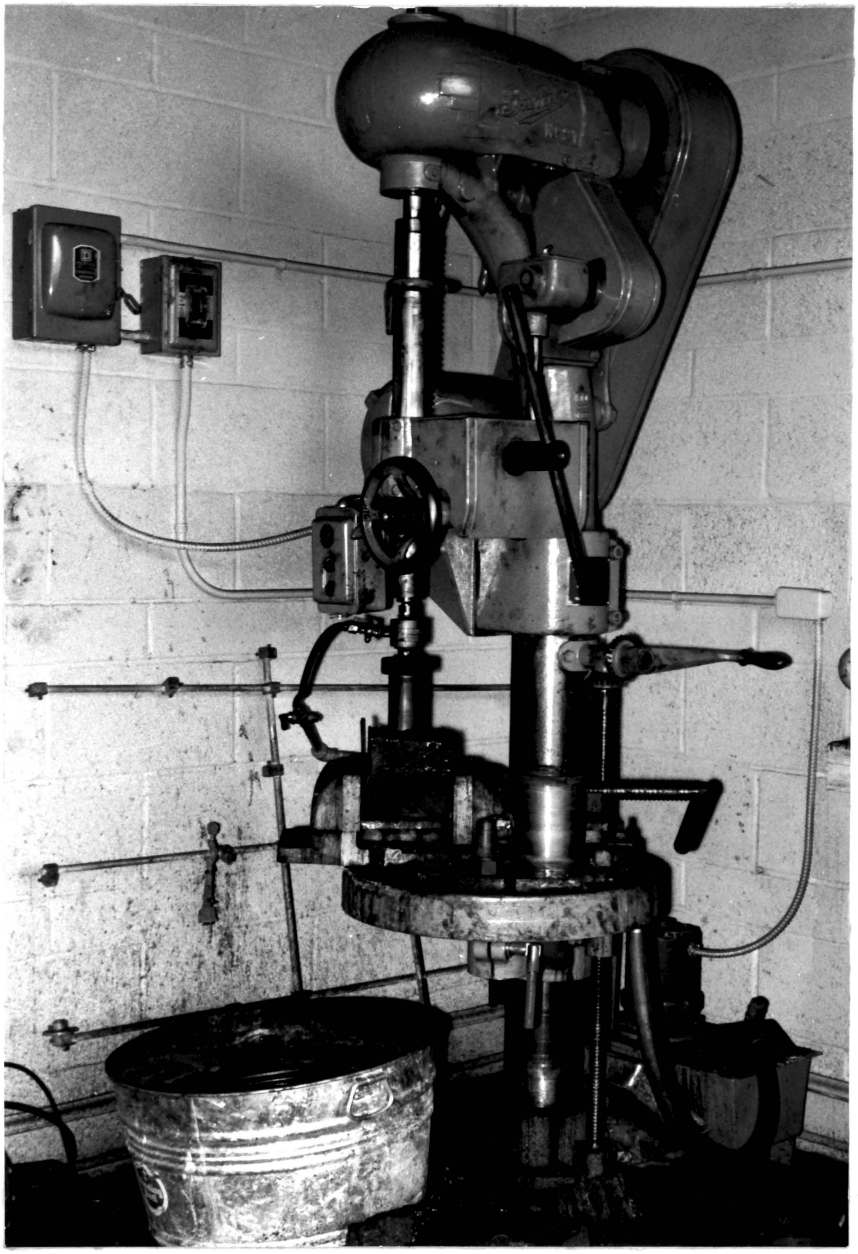

Fig. 6. Buffalo No. 21 Drill Press

and both plates were tightened to the sleeve by clamping bolts. Rubber sheeting was placed between the sleeve and the plates to make the sample holder unit airtight.

The sealing material used to mount the sample to the steel sleeve was chosen to have the following properties: easily poured, rapidly hardened, and no heat envolved that might affect the coal specimen by creating more fractures. For this experiment a bonding agent R-313 (Helix, Epoxy Products) was used. Care was taken to pour the bonding agent around the sample little by little, since a large amount of this agent will release heat in the process of hardening.

C. Method of Testing

The measurement of coal permeability was based on the practice used for permeability measurements of core samples in the oil industry. This practice has been standardized by the American Petroleum Institute.[5] The data obtained gave the values for calculating the permeability value of the sample by using D'Arcy's Law:

$$k_a = \frac{U \bar{Q} L}{A P}$$

in which: k_a is the observed permeability in darcies, U is the air viscosity in centipoise,

$\overline{Q}$ is the flowrate in cubic centimeters per second

P is the mean pressure under which the air flows through the sample, in atmospheres,

L is the length of sample, in centimeters,

A is the cross section of the sample in square centimeters.

The procedure included the correction for gas slippage effect which exists when air is used as the fluid under low pressure.

The following procedure was followed for all measurements:

1. Prior to every measurement the line was checked for leakage by flowing air into the permeameter and then closing the air exhaust line. Airtightness was indicated when the float in any tube of the flowmeter did not give a reading.
2. After a specimen was placed and properly seated in the core holder and before attempting to execute any flow measurements, the system was allowed to remain at the mean pressure for the measurement for ten minutes to insure that a condition of equilibrium flow existed.

3. The permeabilities of each sample were determined at least under three different mean pressures. The average flowrate at each mean pressure was obtained from the tube readings, and using the calibration curve (Figure 7), the flowrate $\overline{Q}$ in cubic centimeters per second was obtained.
4. The values of the mean pressure P were obtained from the readings of the U-tube manometer.
5. The air viscosity U at specified temperatures was obtained from the graph shown in Figure 8.
6. The measurements were double-checked by repeating the test with the mounted sample reversed.
7. From the values of $\overline{Q}$, P, U, L, and A, permeability calculations were made to obtain values of the observed permeabilities k_a which were then plotted against the reciprocal mean pressures. The straight line obtained was then extrapolated to infinite pressure, (that is $\frac{1}{P} = 0$), and by graphical methods the true permeability value k_L was obtained.
8. Using the values of $\overline{Q}$, P, U, L, and A, mathematical computations were made by a digital computer to find the values of k_a, k_L and the constant b. The computer programs are shown in Appendix A.

D. Sample Calculation

To make the calculation of permeability from the experimental data clear, an example was carried through from the original data.

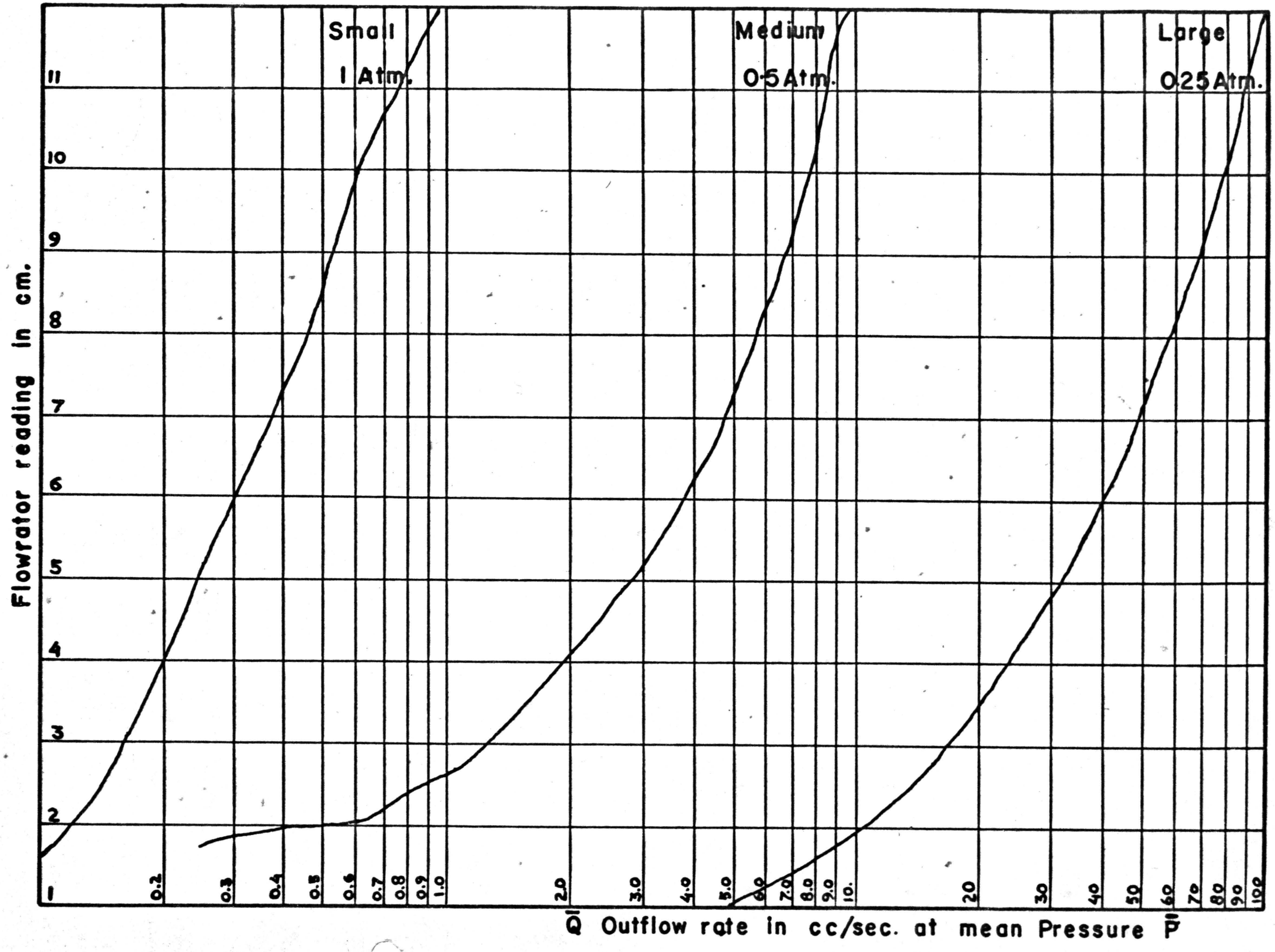

Fig. 7 Ruska Permeameter Calibration Curve

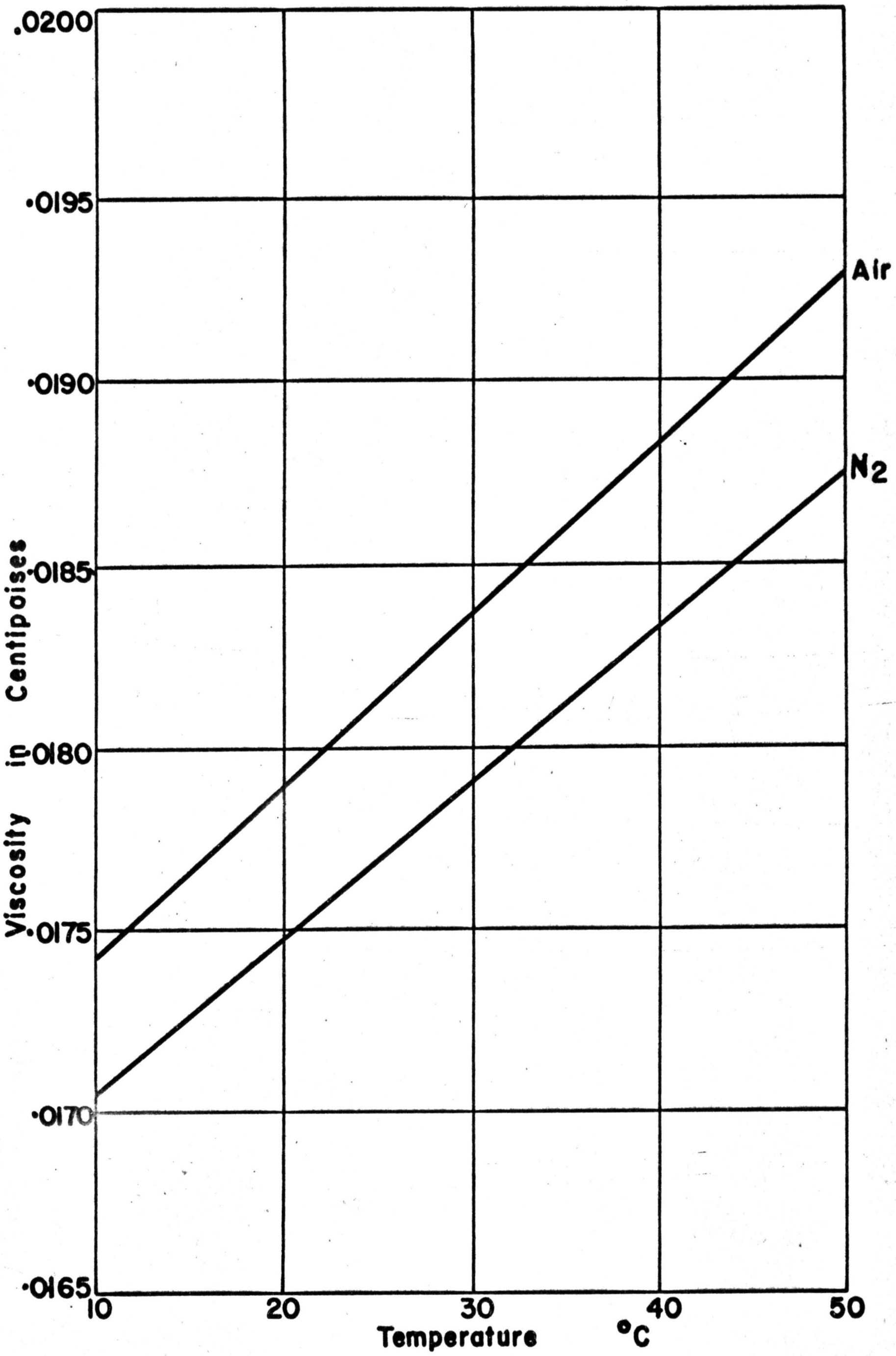

Fig. 8 Gas Viscosity
(from Ruska)

Sample Cr 1-4, Core Sample:

Observed values:

1. Diameter of core = one inch = 2.54 cm.
2. Length of core = 2.537 cm.
3. Temperature = 29° C.
4. Gage readings,

    measurement I: 0.5 atmosphere
    measurement II: 0.6 atmosphere
    measurement III: 0.3 atmosphere

5. Flowrator readings, medium tube:

    measurement I: 29.0 mm
    measurement II: 33.5 mm
    measurement III: 22.0 mm

From Figure 8, the viscosity of the air at 29° C equals 0.0183 centipoise. From Figure 7, curve of the medium tube with reading at 29.0 mm under 0.5 atmosphere gives flowrate of 1.10 cubic centimeters per second. Flowrates of measurements II and III were obtained by proportion from measurement I.

Measurement II, 33.5 mm reading equals $\frac{33.5}{29.0} \times 1.10$ cc/sec.

= 1.27 cc/sec.

Measurement III, 22.0 mm reading = 0.83 cc/sec.

The cross sectional area (A) was calculated from the diameter of the core specimen, and equals 5.064 cm^2.

The downstream pressure in the Ruska permeameter is one atmosphere absolute, so that the pressure gradient is equal to the

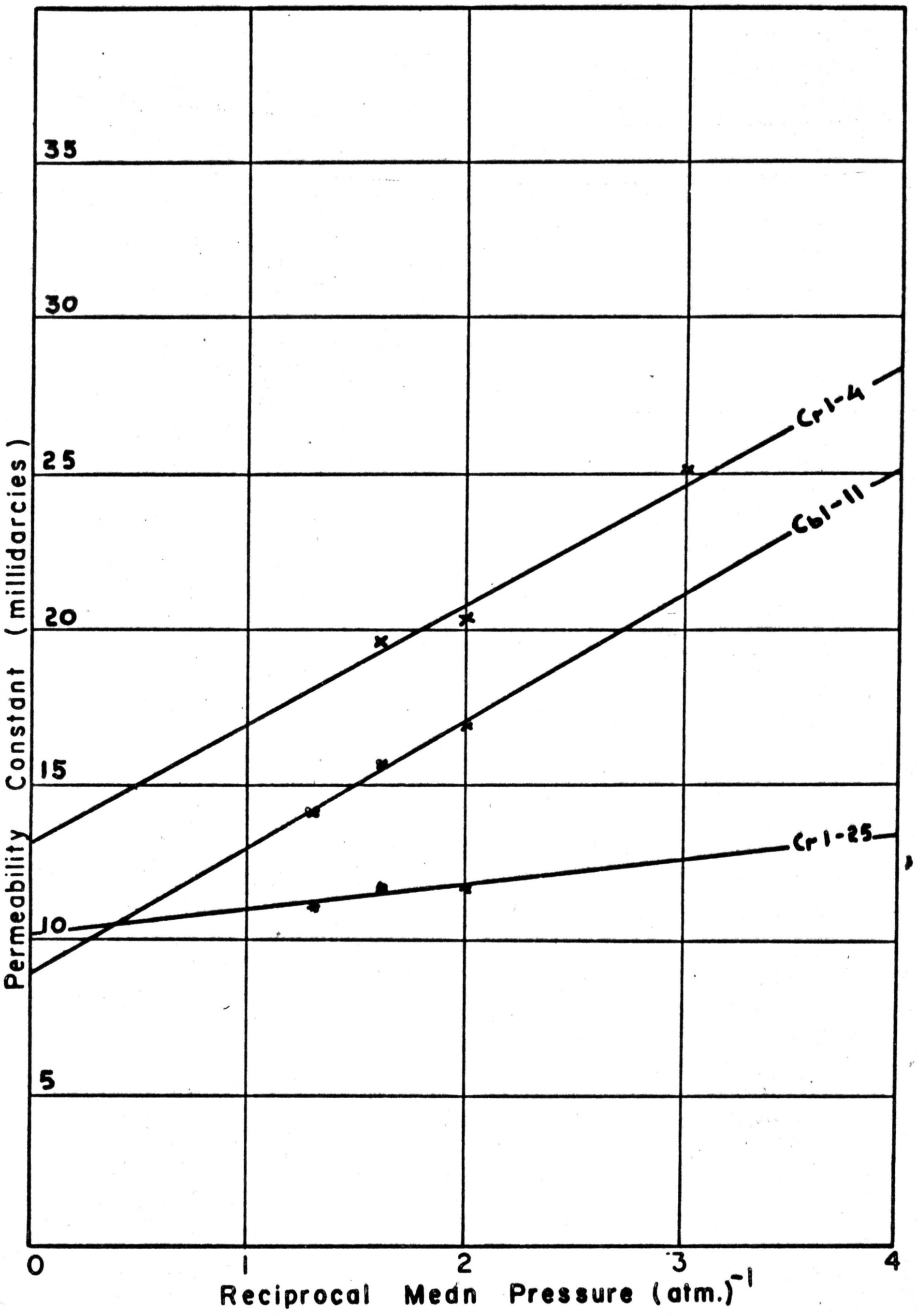

Fig. 9 Graphical Method to Find True Permeability from the Observed Permeability Values.

indicated gage pressure.[20]

For measurement I: $k_a = \frac{U \bar{Q} L}{A \times 0.5}$

$$= \frac{0.0183 \times 1.10 \times 2.537}{5.064 \times 0.5} \quad \text{darcy}$$

$$= 0.02017 \quad \text{darcy}$$

$$= 20.17 \quad \text{millidarcies.}$$

By using the same method,

measurement II: $k_a = 19.41$ millidarcies

measurement III: $k_a = 25.36$ millidarcies.

To obtain the true permeability value k_L, plot k_a against $\frac{1}{P}$, as shown in Figure 9, and by extrapolation k_L was found 13.20 millidarcies.

E. Mathematical Solution

The computer programs shown in Appendix A were prepared based upon the assumption that the gas permeability is a linear function of the reciprocal mean pressure, as stated by Klinkenberg [3]:

$$k_a = k_L + \frac{k_L b}{P}$$

Using the Least Square Method, if a straight line trend is assumed, the line of trend will have a formula: Y = A + B X In this formula the values of A and B must be determined. These two unknowns can be determined by the use of the following two equations [21]:

$$\text{I.} \quad \Sigma(Y) = N\,A + B\,\Sigma(X)$$

$$\text{II.} \quad \Sigma(X\,Y) = A\,\Sigma(X) + B\,\Sigma(X^2)$$

By analogy, the values of k_L and b of the Klinkenberg equation could be solved, in which:

$$k_a = Y$$

$$k_L = A$$

$$\frac{1}{P} = X$$

$$k_L\, b = B$$

N is the number of tests run on one sample under different values of mean pressure.

The values of k_a were computed by using the formula:

$$k_a = 1000 \times \frac{U\,\bar{Q}\,L}{A\,P} \text{ millidarcies.}$$

The predicted values of apparent permeability were obtained by substituting the computed values of k_L and b into the original equation $k_a = k_L\,(1 + \frac{b}{P})$ with varying pressures.

The per cent different values:

$$\text{Per cent Different} = 100 \times \frac{\text{Observed } k_a - \text{Predicted } k_a}{\text{Observed } k_a}$$

show how far the observed permeability values are from the predicted values.

IV. EXPERIMENTAL RESULTS

Coal possesses a stratified structure and consists of component layers of vitrain, durain, clarain and fusain, which occur in planes parallel to the bedding plane. Because of this heterogeneous nature of coal, unique values for permeability cannot be obtained and many measurements were required for representative evaluation.

A total of 113 coal specimens of different geometrical dimensions and shapes were tested. Table 1 shows the data from laboratory observations, and the values of both observed or apparent and true permeability and the constant b *) as computed by the digital computer. A graphical method for determining the values of the true permeability k_L is also given and shown in Figures 10 to 13. An example employing the graphical method to obtain the true permeability values is shown in Figure 9. The results of both methods of solution showed insignificant differences.

The Frequency Distribution Diagram of the values of the true permeability obtained from the experiments is shown in Figure 14.

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*) Due to the limitation of the computer, the value b was printed and shown in Table 1 as B.

The apparent permeability values shown in Table 1 are the values obtained by computations of the values from the flowrate measurements. The predicted apparent permeability values were obtained by substituting the computed k_L and b into the original equation : $k_a = k_L \left(1 + \frac{b}{P} \right)$.

Some examples of the typical differences between the results of graphical and computer method of solution are:

Figure 10, one-inch specimen, Core 1-4

Graphical method, $k_L = 13.6$ millidarcies

By computer, $k_L = 13.09$ millidarcies.

Figure 12, three-inch specimen, Cube 3-9

Graphical method, $k_L = 54.0$ millidarcies

By computer, $k_L = 52.44$ millidarcies.

TABLE 1. RESULTS OF PERMEABILITY MEASUREMENTS

SAMPLE NUMBER	LENGTH (CM)	CROSS SECTION (SQ CM)	PRESSURE (ATMS)	FLOWRATE (CC/SEC)	PERMEABILITY (MILLIDARCIES)		B	PREDICTED APPARENT PERMEABIL	PCT DIFF
					APPARENT	TRUE			
CORE 1-1	2.593	5.064	0.30	1.64	51.225	18.84	0.516	51.285	0.12
			0.50	2.06	38.606			38.309	-0.77
			0.60	2.23	34.827			35.065	0.68
CORE 1-2	3.033	5.064	0.50	0.84	18.162	13.38	0.183	18.272	0.61
			0.60	0.98	17.658			17.457	-1.13
			0.75	1.15	16.576			16.642	0.40
			0.95	1.40	15.932			15.956	0.15
CORE 1-3	2.987	5.064	0.50	0.33	7.027	5.87	0.098	7.016	-0.16
			0.60	0.39	6.920			6.825	-1.38
			0.75	0.45	6.388			6.634	3.85
			0.95	0.59	6.612			6.473	-2.11
CORE 1-4	2.537	5.064	0.30	0.83	25.365	13.09	0.280	25.314	-0.20
			0.50	1.10	20.170			20.424	1.26
			0.60	1.27	19.406			19.202	-1.05

TABLE 1. (Cont'd)

SAMPLE NUMBER	LENGTH (CM)	CROSS SECTION (SQ CM)	PRESSURE (ATMS)	FLOWRATE (CC/SEC)	PERMEABILITY (MILLIDARCIES)		B	PREDICTED APPARENT PERMEABIL	PCT DIFF
					APPARENT	TRUE			
CORE 1-5	2.433	5.064	0.50	0.43	7.458	4.99	0.251	7.498	0.53
			0.60	0.50	7.227			7.080	-2.03
			0.75	0.56	6.475			6.662	2.89
			0.95	0.70	6.390			6.310	-1.25
CORE 1-6	2.020	5.064	0.50	0.50	7.260	6.03	0.091	7.126	-1.84
			0.60	0.56	6.776			6.944	2.48
			0.75	0.69	6.679			6.761	1.23
			0.95	0.88	6.725			6.608	-1.74
CORE 1-7	2.995	5.064	0.50	0.74	16.062	8.86	0.416	16.243	1.13
			0.60	0.85	15.375			15.013	-2.35
			0.75	0.94	13.602			13.783	1.33
CORE 1-8	3.188	5.064	0.50	0.44	10.000	6.77	0.235	9.953	-0.46
			0.60	0.50	9.469			9.423	-0.49
			0.75	0.57	8.636			8.893	2.98
			0.95	0.72	8.612			8.447	-1.91

TABLE 1. (Cont'd)

SAMPLE NUMBER	LENGTH (CM)	CROSS SECTION (SQ CM)	PRESSURE (ATMS)	FLOWRATE (CC/SEC)	PERMEABILITY (MILLIDARCIES)		B	PREDICTED APPARENT PERMEABIL	PCT DIFF
					APPARENT	TRUE			
CUBE 1-9	2.560	6.130	0.30	2.12	54.154	24.35	0.370	54.344	0.35
			0.50	2.80	42.914			42.345	-1.33
			0.75	3.52	35.966			36.346	1.06
CORE 1-10	3.090	5.064	0.30	1.46	54.492	23.55	0.400	54.924	0.79
			0.50	1.95	43.668			42.373	-2.97
			0.75	2.36	35.233			36.097	2.45
CUBE 1-11	2.819	5.859	0.50	0.96	16.998	8.90	0.457	17.047	0.29
			0.60	1.07	15.788			15.689	-0.62
			0.75	1.21	14.283			14.332	0.34
CORE 1-12	2.296	5.064	0.50	0.76	12.681	5.37	0.684	12.708	0.22
			0.60	0.83	11.540			11.485	-0.48
			0.75	0.92	10.233			10.261	0.27

TABLE 1. (Cont'd)

SAMPLE NUMBER	LENGTH (CM)	CROSS SECTION (SQ CM)	PRESSURE (ATMS)	FLOWRATE (CC/SEC)	PERMEABILITY (MILLIDARCIES)		B	PREDICTED APPARENT PERMEABIL	PCT DIFF
					APPARENT	TRUE			
CORE 1-13	2.550	5.064	0.50	0.37	6.856	3.77	0.431	7.027	2.48
			0.60	0.43	6.640			6.485	-2.34
			0.75	0.50	6.177			5.943	-3.79
			0.95	0.54	5.267			5.486	4.17
CORE 1-14	2.515	5.064	0.30	0.55	16.753	11.22	0.150	16.833	0.48
			0.50	0.82	14.987			14.588	-2.66
			0.60	0.90	13.707			14.026	2.33
CORE 1-15	2.271	5.064	0.30	2.03	55.836	21.64	0.474	55.823	-0.02
			0.50	2.55	42.083			42.149	0.16
			0.60	2.82	38.783			38.730	-0.14
CORE 1-16	2.436	5.064	0.50	0.37	6.425	3.63	0.397	6.501	1.17
			0.60	0.42	6.078			6.021	-0.93
			0.75	0.49	5.673			5.542	-2.30
			0.95	0.55	5.027			5.139	2.22

TABLE 1. (Cont'd)

SAMPLE NUMBER	LENGTH (CM)	CROSS SECTION (SQ CM)	PRESSURE (ATMS)	FLOWRATE (CC/SEC)	PERMEABILITY (MILLIDARCIES)		B	PREDICTED APPARENT PERMEABIL	PCT DIFF
					APPARENT	TRUE			
CUBE 1-17	2.682	4.721	0.30	0.90	31.478	12.11	0.484	31.648	0.54
			0.50	1.16	24.343			23.834	-2.09
			0.75	1.40	19.587			19.926	1.73
CORE 1-18	2.840	5.064	0.30	2.20	74.440	24.55	0.606	74.129	-0.42
			0.40	2.40	60.905			61.734	1.36
			0.50	2.70	54.815			54.297	-0.94
CORE 1-19	3.183	5.064	0.60	0.47	8.936	3.68	0.869	8.996	0.67
			0.75	0.53	8.062			7.932	-1.61
			0.95	0.58	6.965			7.036	1.01
CORE 1-20	2.720	5.064	0.40	1.00	24.345	11.01	0.482	24.268	-0.32
			0.50	1.10	21.424			21.616	0.90
			0.60	1.23	19.963			19.848	-0.58

TABLE 1. (Cont'd)

SAMPLE NUMBER	LENGTH (CM)	CROSS SECTION (SQ CM)	PRESSURE (ATMS)	FLOWRATE (CC/SEC)	PERMEABILITY (MILLIDARCIES)		B	PREDICTED APPARENT PERMEABIL	PCT DIFF
					APPARENT	TRUE			
CUBE 1-21	2.761	5.498	0.30	1.46	44.969	18.79	0.419	45.013	0.10
			0.50	1.88	34.743			34.523	-0.63
			0.60	2.06	31.725			31.901	0.55
CUBE 1-22	2.708	5.853	0.50	0.50	8.328	7.26	0.053	8.031	-3.57
			0.60	0.54	7.495			7.903	5.44
			0.75	0.69	7.662			7.775	1.47
			0.95	0.90	7.890			7.667	-2.82
CUBE 1-23	2.570	5.763	0.30	2.26	61.814	21.38	0.569	61.900	0.14
			0.50	2.80	45.951			45.693	-0.56
			0.75	3.42	37.417			37.589	0.46
CORE 1-24	2.593	5.064	0.30	0.62	19.545	9.40	0.325	19.604	0.30
			0.50	0.83	15.699			15.524	-1.12
			0.75	1.06	13.367			13.484	0.88

TABLE 1. (Cont'd)

SAMPLE NUMBER	LENGTH (CM)	CROSS SECTION (SQ CM)	PRESSURE (ATMS)	FLOWRATE (CC/SEC)	PERMEABILITY (MILLIDARCIES)		B	PREDICTED APPARENT PERMEABIL	PCT DIFF
					APPARENT	TRUE			
CORE 1-25	2.395	5.064	0.50	0.68	11.642	10.32	0.066	11.690	0.41
			0.60	0.81	11.556			11.461	-0.82
			0.75	0.98	11.185			11.233	0.43
CORE 1-26	2.929	5.064	0.50	0.64	13.363	13.32	0.000	13.317	-0.35
			0.60	0.76	13.224			13.317	0.70
			0.75	0.96	13.363			13.317	-0.35
CORE 1-27	2.962	5.064	0.30	0.62	22.327	10.74	0.325	22.394	0.30
			0.50	0.83	17.934			17.733	-1.12
			0.75	1.06	15.269			15.402	0.88
CORE 1-28	2.515	5.064	0.50	0.34	6.096	4.33	0.222	6.256	2.63
			0.60	0.41	6.126			5.935	-3.11
			0.75	0.48	5.737			5.614	-2.15
			0.95	0.55	5.190			5.344	2.96

TABLE 1. (Cont'd)

SAMPLE NUMBER	LENGTH (CM)	CROSS SECTION (SQ CM)	PRESSURE (ATMS)	FLOWRATE (CC/SEC)	PERMEABILITY (MILLIDARCIES)		B	PREDICTED APPARENT PERMEABIL	PCT DIFF
					APPARENT	TRUE			
CORE 1-29	2.840	5.064	0.50	0.53	10.790	9.31	0.091	11.003	1.97
			0.60	0.64	10.858			10.720	-1.26
			0.75	0.80	10.858			10.438	-3.86
			0.95	0.92	9.857			10.201	3.48
CUBE 1-30	2.918	5.887	0.50	1.10	19.628	7.62	0.796	19.757	0.66
			0.60	1.21	17.993			17.735	-1.43
			0.75	1.31	15.584			15.713	0.83
CUBE 1-31	2.928	5.946	0.50	0.70	12.478	5.68	0.596	12.458	-0.16
			0.60	0.76	11.290			11.329	0.35
			0.75	0.86	10.220			10.200	-0.19
CUBE 1-32	2.816	6.187	0.40	2.22	45.469	22.23	0.419	45.512	0.09
			0.50	2.50	40.963			40.856	-0.26
			0.60	2.76	37.686			37.751	0.17

TABLE 1. (Cont'd)

SAMPLE NUMBER	LENGTH (CM)	CROSS SECTION (SQ CM)	PRESSURE (ATMS)	FLOWRATE (CC/SEC)	PERMEABILITY (MILLIDARCIES)		B	PREDICTED APPARENT PERMEABIL	PCT DIFF
					APPARENT	TRUE			
CORE 1-33	2.860	5.064	0.60	0.60	10.194	4.14	0.883	10.235	0.41
			0.75	0.67	9.107			9.016	-0.99
			0.95	0.74	7.941			7.990	0.62
CORE 1-34	2.364	5.064	0.40	1.66	35.066	21.75	0.243	34.977	-0.25
			0.50	1.90	32.108			32.331	0.69
			0.60	2.18	30.700			30.567	-0.43
CUBE 1-35	2.631	5.548	0.50	0.52	8.927	6.13	0.228	8.922	-0.05
			0.60	0.59	8.440			8.457	0.19
			0.75	0.70	8.011			7.991	-0.26
			0.95	0.84	7.590			7.598	0.12
CUBE 1-36	2.695	5.030	0.50	0.35	6.826	4.98	0.192	6.886	0.87
			0.60	0.41	6.663			6.567	-1.44
			0.75	0.48	6.241			6.249	0.13
			0.95	0.58	5.953			5.981	0.47

TABLE 1. (Cont'd)

SAMPLE NUMBER	LENGTH (CM)	CROSS SECTION (SQ CM)	PRESSURE (ATMS)	FLOWRATE (CC/SEC)	PERMEABILITY (MILLIDARCIES)		B	PREDICTED APPARENT PERMEABIL	PCT DIFF
					APPARENT	TRUE			
CUBE 1-37	2.878	5.465	0.30	5.20	165.219	66.72	0.443	165.219	0.00
			0.40	5.90	140.595			140.595	-0.00
			0.50	6.60	125.821			125.821	-0.00
CORE 1-38	2.708	5.064	0.30	2.88	93.946	30.99	0.609	93.899	-0.05
			0.50	3.50	68.502			68.735	0.34
			0.60	3.84	62.631			62.444	-0.30
CORE 1-39	2.930	5.064	0.30	2.92	103.059	35.76	0.565	103.076	0.02
			0.50	3.60	76.236			76.152	-0.11
			0.60	3.93	69.353			69.420	0.10
CORE 1-40	2.886	5.064	0.30	5.50	191.203	66.94	0.555	190.884	-0.17
			0.40	6.10	159.046			159.898	0.54
			0.50	6.80	141.838			141.306	-0.38

TABLE 1. (Cont'd)

SAMPLE NUMBER	LENGTH (CM)	CROSS SECTION (SQ CM)	PRESSURE (ATMS)	FLOWRATE (CC/SEC)	PERMEABILITY (MILLIDARCIES)		B	PREDICTED APPARENT PERMEABIL	PCT DIFF
					APPARENT	TRUE			
CUBE 1-41	2.997	5.836	0.30	5.00	156.629	75.18	0.325	156.629	-0.00
			0.40	5.80	136.267			136.267	0.00
			0.50	6.60	124.050			124.050	0.00
CUBE 1-42	2.929	5.988	0.30	2.71	81.302	28.40	0.559	81.331	0.04
			0.50	3.35	60.302			60.159	-0.24
			0.60	3.65	54.752			54.866	0.21
CORE 2-1	5.364	20.258	0.25	7.50	144.016	69.01	0.270	143.625	-0.27
			0.30	8.20	131.215			131.189	-0.02
			0.40	9.50	114.013			115.644	1.43
			0.50	11.20	107.532			106.317	-1.13
CUBE 2-2	5.502	28.349	0.25	5.80	81.273	44.08	0.210	81.029	-0.30
			0.30	6.40	74.734			74.870	0.18
			0.40	7.60	66.560			67.172	0.92
			0.50	9.00	63.057			62.553	-0.80

TABLE 1. (Cont'd)

SAMPLE NUMBER	LENGTH (CM)	CROSS SECTION (SQ CM)	PRESSURE (ATMS)	FLOWRATE (CC/SEC)	PERMEABILITY (MILLIDARCIES)		B	PREDICTED APPARENT PERMEABIL	PCT DIFF
					APPARENT	TRUE			
CORE 2-3	4.552	20.258	0.25	1.67	27.168	12.10	0.312	27.215	0.17
			0.50	2.45	19.929			19.659	-1.36
			0.60	2.69	18.234			18.399	0.91
			0.75	3.15	17.082			17.140	0.34
CORE 2-4	6.467	20.258	0.30	3.71	71.456	42.00	0.214	71.904	0.63
			0.40	4.55	65.726			64.428	-1.98
			0.50	5.10	58.937			59.942	1.71
			0.60	5.93	57.107			56.952	-0.27
CUBE 2-5	5.410	23.803	0.30	4.63	63.841	37.05	0.218	64.005	0.26
			0.40	5.58	57.705			57.266	-0.76
			0.50	6.40	52.948			53.222	0.52
CORE 2-6	4.935	20.258	0.40	2.14	23.720	11.94	0.386	23.450	-1.14
			0.50	2.35	20.838			21.148	1.49
			0.60	2.61	19.286			19.613	1.69
			0.75	3.12	18.444			18.078	-1.98

TABLE 1. (Cont'd)

SAMPLE NUMBER	LENGTH (CM)	CROSS SECTION (SQ CM)	PRESSURE (ATMS)	FLOWRATE (CC/SEC)	PERMEABILITY (MILLIDARCIES)		B	PREDICTED APPARENT PERMEABIL	PCT DIFF
					APPARENT	TRUE			
CUBE 2-7	5.517	22.716	0.30	1.50	22.040	10.34	0.347	22.291	1.14
			0.50	2.08	18.338			17.510	-4.51
			0.60	2.20	16.163			16.314	0.94
			0.75	2.50	14.694			15.119	2.90
CUBE 2-8	4.816	22.531	0.25	10.00	154.327	90.10	0.179	154.486	0.10
			0.30	11.20	144.039			143.754	-0.20
			0.40	13.50	130.214			130.340	0.10
CORE 2-9	5.258	20.258	0.50	3.40	31.946	18.57	0.369	32.290	1.08
			0.60	3.92	30.693			30.004	-2.24
			0.75	4.37	27.373			27.718	1.26
CORE 2-10	5.595	20.258	0.50	1.63	16.297	10.81	0.254	16.308	0.07
			0.60	1.85	15.414			15.391	-0.14
			0.75	2.17	14.464			14.475	0.08

TABLE 1. (Cont'd)

SAMPLE NUMBER	LENGTH (CM)	CROSS SECTION (SQ CM)	PRESSURE (ATMS)	FLOWRATE (CC/SEC)	PERMEABILITY (MILLIDARCIES)		B	PREDICTED APPARENT PERMEABIL	PCT DIFF
					APPARENT	TRUE			
CORE 2-11	4.709	20.258	0.50	5.60	47.123	24.07	0.483	47.291	0.36
			0.60	6.24	43.757			43.420	-0.77
			0.75	7.02	39.381			39.549	0.43
CORE 2-12	4.859	20.258	0.50	1.80	15.629	5.87	0.843	15.769	0.90
			0.60	1.99	14.399			14.119	-1.94
			0.75	2.13	12.330			12.469	1.13
CUBE 2-13	5.098	21.506	0.50	1.40	12.047	7.07	0.353	12.061	0.12
			0.60	1.57	11.258			11.229	-0.25
			0.75	1.81	10.383			10.398	0.14
CUBE 2-14	4.648	20.395	0.30	1.83	25.232	9.77	0.475	25.229	-0.01
			0.50	2.30	19.027			19.044	0.09
			0.60	2.54	17.511			17.497	-0.07

TABLE 1. (Cont'd)

SAMPLE NUMBER	LENGTH (CM)	CROSS SECTION (SQ CM)	PRESSURE (ATMS)	FLOWRATE (CC/SEC)	PERMEABILITY (MILLIDARCIES)		B	PREDICTED APPARENT PERMEABIL	PCT DIFF
					APPARENT	TRUE			
CORE 2-15	6.022	20.258	0.25	8.50	183.948	70.55	0.403	184.413	0.25
			0.30	9.22	166.274			165.436	-0.50
			0.40	10.45	141.342			141.715	0.26
CORE 2-16	4.531	20.258	0.40	1.24	12.515	10.15	0.094	12.536	0.17
			0.50	1.50	12.111			12.058	-0.44
			0.60	1.74	11.708			11.740	0.27
CORE 2-17	6.485	20.258	0.40	5.90	85.228	46.23	0.337	85.228	-0.00
			0.50	6.70	77.428			77.428	0.00
			0.60	7.50	72.227			72.227	0.00
CORE 2-18	5.489	20.258	0.20	9.50	235.141	72.30	0.448	234.360	-0.33
			0.25	10.10	199.994			201.948	0.98
			0.30	11.00	181.513			180.340	-0.65

TABLE 1. (Cont'd)

SAMPLE NUMBER	LENGTH (CM)	CROSS SECTION (SQ CM)	PRESSURE (ATMS)	FLOWRATE (CC/SEC)	PERMEABILITY (MILLIDARCIES)		B	PREDICTED APPARENT PERMEABIL	PCT DIFF
					APPARENT	TRUE			
CORE 2-19	5.514	20.258	0.20	8.00	198.698	99.35	0.200	198.698	-0.00
			0.25	9.00	178.828			178.828	-0.00
			0.30	10.00	165.581			165.581	-0.00
CORE 2-20	5.250	20.258	0.20	10.75	254.217	120.29	0.222	254.092	-0.05
			0.25	12.00	227.021			227.333	0.14
			0.30	13.30	209.680			209.493	-0.09
CUBE 2-21	5.168	24.439	0.40	2.30	22.045	13.38	0.256	21.954	-0.41
			0.50	2.61	20.013			20.240	1.13
			0.60	3.01	19.233			19.097	-0.71
CUBE 2-22	5.113	25.048	0.40	3.60	33.308	20.60	0.249	33.405	0.29
			0.50	4.20	31.087			30.844	-0.78
			0.60	4.70	28.990			29.136	0.50

TABLE 1. (Con'd)

SAMPLE NUMBER	LENGTH (CM)	CROSS SECTION (SQ CM)	PRESSURE (ATMS)	FLOWRATE (CC/SEC)	PERMEABILITY (MILLIDARCIES) APPARENT	PERMEABILITY (MILLIDARCIES) TRUE	B	PREDICTED APPARENT PERMEABIL	PCT DIFF
CUBE 2-23	5.468	30.042	0.25	14.00	184.793	96.67	0.227	184.522	-0.15
			0.30	15.40	169.394			169.880	0.29
			0.40	18.40	151.794			151.578	-0.14
CUBE 2-24	4.859	26.887	0.25	9.00	118.082	54.68	0.290	118.109	0.02
			0.30	9.84	107.586			107.537	-0.04
			0.40	11.50	94.302			94.323	0.02
CUBE 2-25	4.544	23.537	0.25	6.00	84.096	50.46	0.167	84.096	-0.00
			0.30	6.72	78.490			78.490	-0.00
			0.40	8.16	71.482			71.482	0.00
CUBE 2-26	4.905	19.214	0.30	5.89	91.219	48.60	0.262	91.063	-0.17
			0.40	6.89	80.030			80.447	0.52
			0.50	8.00	74.338			74.078	-0.35

TABLE 1. (Cont'd)

SAMPLE NUMBER	LENGTH (CM)	CROSS SECTION (SQ CM)	PRESSURE (ATMS)	FLOWRATE (CC/SEC)	PERMEABILITY (MILLIDARCIES)		B	PREDICTED APPARENT PERMEABIL	PCT DIFF
					APPARENT	TRUE			
CUBE 2-27	4.178	21.797	0.40	5.42	47.270	20.08	0.542	47.279	0.02
			0.50	6.00	41.862			41.839	-0.05
			0.60	6.57	38.199			38.213	0.04
CUBE 2-28	5.237	26.637	0.40	2.20	19.572	14.74	0.131	19.563	-0.05
			0.50	2.61	18.576			18.599	0.13
			0.60	3.03	17.971			17.957	-0.08
CUBE 2-29	5.265	27.726	0.25	14.00	194.072	110.90	0.187	194.072	-0.00
			0.30	15.60	180.209			180.209	-0.00
			0.40	18.80	162.882			162.882	0.00
CUBE 2-30	5.512	25.065	0.30	5.49	73.444	38.03	0.278	73.333	-0.15
			0.40	6.40	64.213			64.508	0.46
			0.50	7.40	59.397			59.213	-0.31

TABLE 1. (Cont'd)

SAMPLE NUMBER	LENGTH (CM)	CROSS SECTION (SQ CM)	PRESSURE (ATMS)	FLOWRATE (CC/SEC)	PERMEABILITY (MILLIDARCIES)		B	PREDICTED APPARENT PERMEABIL	PCT DIFF
					APPARENT	TRUE			
CUBE 2-31	4.671	25.246	0.25	11.40	153.551	58.43	0.408	153.689	0.09
			0.30	12.30	138.061			137.813	-0.18
			0.40	14.00	117.857			117.968	0.09
CUBE 3-1	8.008	54.697	0.25	13.00	136.656	100.17	0.093	137.302	0.47
			0.30	15.10	132.276			131.113	-0.88
			0.40	18.70	122.859			123.376	0.42
CUBE 3-2	7.785	56.243	0.25	9.00	89.445	65.40	0.092	89.394	-0.06
			0.30	10.30	85.304			85.396	0.11
			0.40	12.95	80.439			80.398	-0.05
CUBE 3-3	7.219	48.836	0.25	21.00	224.747	135.97	0.165	225.625	0.39
			0.30	23.80	212.261			210.682	-0.74
			0.40	28.60	191.303			192.005	0.37

TABLE 1. (Cont'd)

SAMPLE NUMBER	LENGTH (CM)	CROSS SECTION (SQ CM)	PRESSURE (ATMS)	FLOWRATE (CC/SEC)	PERMEABILITY (MILLIDARCIES)		B	PREDICTED APPARENT PERMEABIL	PCT DIFF
					APPARENT	TRUE			
CUBE 3-4	8.096	62.977	0.25	21.00	194.915	139.89	0.101	196.341	0.73
			0.30	24.50	189.501			186.933	-1.35
			0.40	30.00	174.031			175.172	0.66
CUBE 3-5	7.358	62.849	0.25	13.00	109.886	78.81	0.098	109.713	-0.16
			0.30	14.80	104.251			104.563	0.30
			0.40	18.60	98.263			98.125	-0.14
CUBE 3-6	7.826	64.214	0.25	16.90	148.708	108.57	0.093	148.798	0.06
			0.30	19.40	142.255			142.093	-0.11
			0.40	24.30	133.639			133.711	0.05
CUBE 3-7	7.742	61.034	0.25	11.40	104.116	59.63	0.189	104.678	0.54
			0.30	12.90	98.180			97.169	-1.03
			0.40	15.30	87.334			87.784	0.51

TABLE 1. (Cont'd)

SAMPLE NUMBER	LENGTH (CM)	CROSS SECTION (SQ CM)	PRESSURE (ATMS)	FLOWRATE (CC/SEC)	PERMEABILITY (MILLIDARCIES)		B	PREDICTED APPARENT PERMEABIL	PCT DIFF
					APPARENT	TRUE			
CUBE 3-8	7.998	66.357	0.25	20.50	178.396	121.96	0.116	178.664	0.15
			0.30	23.40	169.694			169.213	-0.28
			0.40	28.90	157.184			157.398	0.14
CUBE 3-9	7.861	54.268	0.25	9.80	102.778	52.44	0.240	102.778	-0.00
			0.30	10.80	94.388			94.388	-0.00
			0.40	12.80	83.900			83.900	0.00
CUBE 3-10	8.136	50.716	0.25	21.50	249.024	119.41	0.270	248.431	-0.24
			0.30	23.40	225.859			226.927	0.47
			0.40	27.70	200.522			200.048	-0.24
CUBE 3-11	8.682	60.116	0.25	22.00	228.763	137.01	0.168	228.976	0.09
			0.30	24.70	214.032			213.648	-0.18
			0.40	29.90	194.318			194.489	0.09

TABLE 1. (Cont'd)

SAMPLE NUMBER	LENGTH (CM)	CROSS SECTION (SQ CM)	PRESSURE (ATMS)	FLOWRATE (CC/SEC)	PERMEABILITY (MILLIDARCIES)		B	PREDICTED APPARENT PERMEABIL	PCT DIFF
					APPARENT	TRUE			
CUBE 3-12	8.641	65.477	0.25	17.00	162.429	103.69	0.143	162.820	0.24
			0.30	19.30	153.670			152.965	-0.46
			0.40	23.50	140.334			140.647	0.22
CUBE 3-13	7.932	58.484	0.25	20.50	200.741	115.64	0.183	200.240	-0.25
			0.30	22.70	185.237			186.140	0.49
			0.40	27.60	168.916			168.515	-0.24
CUBE 3-14	7.153	49.997	0.25	22.30	230.987	134.55	0.179	231.125	0.06
			0.30	24.94	215.277			215.029	-0.12
			0.40	30.09	194.798			194.909	0.06
CUBE 3-15	7.777	61.588	0.25	11.00	100.843	50.78	0.247	100.965	0.12
			0.30	12.15	92.821			92.602	-0.24
			0.40	14.32	82.049			82.147	0.12

TABLE 1. (Cont'd)

SAMPLE NUMBER	LENGTH (CM)	CROSS SECTION (SQ CM)	PRESSURE (ATMS)	FLOWRATE (CC/SEC)	PERMEABILITY (MILLIDARCIES)		B	PREDICTED APPARENT PERMEABIL	PCT DIFF
					APPARENT	TRUE			
CUBE 3-16	7.694	56.991	0.25	12.70	123.790	62.49	0.246	124.030	0.19
			0.30	14.06	114.206			113.774	-0.38
			0.40	16.54	100.762			100.954	0.19
CORE 4-1	10.820	81.032	0.25	20.00	193.348	135.76	0.108	194.239	0.46
			0.30	23.10	186.097			184.493	-0.86
			0.40	28.40	171.596			172.309	0.42
CUBE 4-2	10.472	80.763	0.25	10.00	93.876	49.98	0.219	93.684	-0.20
			0.30	11.00	86.053			86.399	0.40
			0.40	13.20	77.448			77.294	-0.20
CORE 4-3	9.218	81.032	0.25	9.60	79.066	45.30	0.186	79.066	-0.00
			0.30	10.70	73.438			73.438	-0.00
			0.40	12.90	66.403			66.403	0.00

TABLE 1. (Cont'd)

SAMPLE NUMBER	LENGTH (CM)	CROSS SECTION (SQ CM)	PRESSURE (ATMS)	FLOWRATE (CC/SEC)	PERMEABILITY (MILLIDARCIES)		B	PREDICTED APPARENT PERMEABIL	PCT DIFF
					APPARENT	TRUE			
CUBE 4-4	9.548	74.530	0.25	20.00	184.990	132.89	0.099	185.653	0.36
			0.30	23.10	178.053			176.859	-0.67
			0.40	28.60	165.335			165.866	0.32
CORE 4-5	11.356	81.032	0.25	9.40	95.902	48.58	0.243	95.824	-0.08
			0.40	12.20	77.793			78.107	0.40
			0.50	14.20	72.437			72.201	-0.33
CORE 4-6	9.380	81.032	0.25	20.50	172.281	110.42	0.141	172.840	0.32
			0.30	23.30	163.176			162.436	-0.45
			0.40	28.50	149.695			149.432	-0.18
			0.50	33.60	141.186			141.630	0.31
CORE 4-7	10.696	81.032	0.25	12.00	114.362	66.57	0.178	114.069	-0.26
			0.30	13.30	105.626			106.154	0.50
			0.40	16.20	96.493			96.259	-0.24

TABLE 1. (Cont'd)

SAMPLE NUMBER	LENGTH (CM)	CROSS SECTION (SQ CM)	PRESSURE (ATMS)	FLOWRATE (CC/SEC)	PERMEABILITY (MILLIDARCIES)		B	PREDICTED APPARENT PERMEABIL	PCT DIFF
					APPARENT	TRUE			
CORE 4-8	9.152	81.032	0.20	11.90	122.306	63.99	0.183	122.414	0.09
			0.25	13.50	111.000			110.730	-0.24
			0.30	15.00	102.778			102.940	0.16
CORE 4-9	9.472	81.032	0.20	15.50	164.876	96.01	0.144	164.988	0.07
			0.25	17.80	151.473			151.194	-0.18
			0.30	20.00	141.829			141.997	0.12
CORE 4-10	10.797	81.032	0.25	9.20	89.241	41.94	0.281	89.042	-0.22
			0.30	10.00	80.834			81.192	0.44
			0.40	11.80	71.539			71.380	-0.22
CORE 4-11	10.034	81.032	0.25	7.00	62.756	37.25	0.171	62.764	0.01
			0.40	9.50	53.230			53.196	-0.06
			0.50	11.15	49.981			50.006	0.05

TABLE 1. (Cont'd)

SAMPLE NUMBER	LENGTH (CM)	CROSS SECTION (SQ CM)	PRESSURE (ATMS)	FLOWRATE (CC/SEC)	PERMEABILITY (MILLIDARCIES)		B	PREDICTED APPARENT PERMEABIL	PCT DIFF
					APPARENT	TRUE			
CORE 4-12	10.726	81.032	0.25	8.50	81.909	40.24	0.260	82.106	0.24
			0.30	9.40	75.485			75.129	-0.47
			0.40	11.00	66.250			66.408	0.24
CUBE 4-13	10.304	71.446	0.25	17.50	182.223	124.95	0.115	182.223	0.00
			0.30	19.90	172.678			172.678	-0.00
			0.40	24.70	160.747			160.747	-0.00
CORE 4-14	9.803	81.032	0.25	13.00	113.549	46.38	0.360	113.101	-0.39
			0.30	13.90	101.175			101.980	0.80
			0.40	16.20	88.437			88.079	-0.40
CORE 4-15	10.455	81.032	0.25	16.50	153.705	113.03	0.088	153.037	-0.43
			0.30	18.70	145.166			146.369	0.83
			0.40	23.80	138.568			138.033	-0.39

TABLE 1. (Cont'd)

SAMPLE NUMBER	LENGTH (CM)	CROSS SECTION (SQ CM)	PRESSURE (ATMS)	FLOWRATE (CC/SEC)	PERMEABILITY (MILLIDARCIES)		B	PREDICTED APPARENT PERMEABIL	PCT DIFF
					APPARENT	TRUE			
CORE 4-16	10.529	81.032	0.25	21.50	201.700	131.47	0.134	201.989	0.14
			0.30	24.40	190.755			190.236	-0.27
			0.40	29.90	175.315			175.546	0.13
CORE 4-17	10.326	81.032	0.25	21.50	197.811	122.72	0.153	197.906	0.05
			0.30	24.20	185.544			185.374	-0.09
			0.40	29.50	169.635			169.710	0.04
CUBE 4-18	9.461	71.722	0.25	21.00	200.559	134.25	0.126	201.733	0.59
			0.30	24.20	192.600			190.487	-1.10
			0.40	29.40	175.489			176.429	0.54
CUBE 4-19	9.637	80.527	0.25	26.00	225.275	131.24	0.178	224.920	-0.16
			0.30	28.90	208.668			209.307	0.31
			0.40	35.10	190.075			189.791	-0.15

TABLE 1. (Cont'd)

SAMPLE NUMBER	LENGTH (CM)	CROSS SECTION (SQ CM)	PRESSURE (ATMS)	FLOWRATE (CC/SEC)	PERMEABILITY (MILLIDARCIES)		B	PREDICTED APPARENT PERMEABIL	PCT DIFF
					APPARENT	TRUE			
CUBE 4-20	8.758	69.565	0.25	24.50	222.699	136.22	0.158	222.419	-0.13
			0.30	27.40	207.549			208.052	0.24
			0.40	33.50	190.316			190.093	-0.12
CUBE 4-21	9.309	80.592	0.25	27.30	227.673	140.60	0.155	227.536	-0.06
			0.30	30.62	212.800			213.046	0.12
			0.40	37.42	195.044			194.934	-0.06
CUBE 4-22	9.332	79.556	0.25	9.50	80.680	40.97	0.241	80.506	-0.22
			0.30	10.40	73.602			73.916	0.43
			0.40	12.40	65.818			65.678	-0.21
CUBE 4-23	10.264	78.178	0.25	8.50	81.019	44.44	0.205	80.921	-0.12
			0.30	9.40	74.665			74.840	0.24
			0.40	11.30	67.317			67.239	-0.12
CUBE 4-24	9.521	80.664	0.25	18.50	157.656	99.26	0.146	157.307	-0.22
			0.30	20.70	147.004			147.633	0.43
			0.40	25.50	135.819			135.539	-0.21

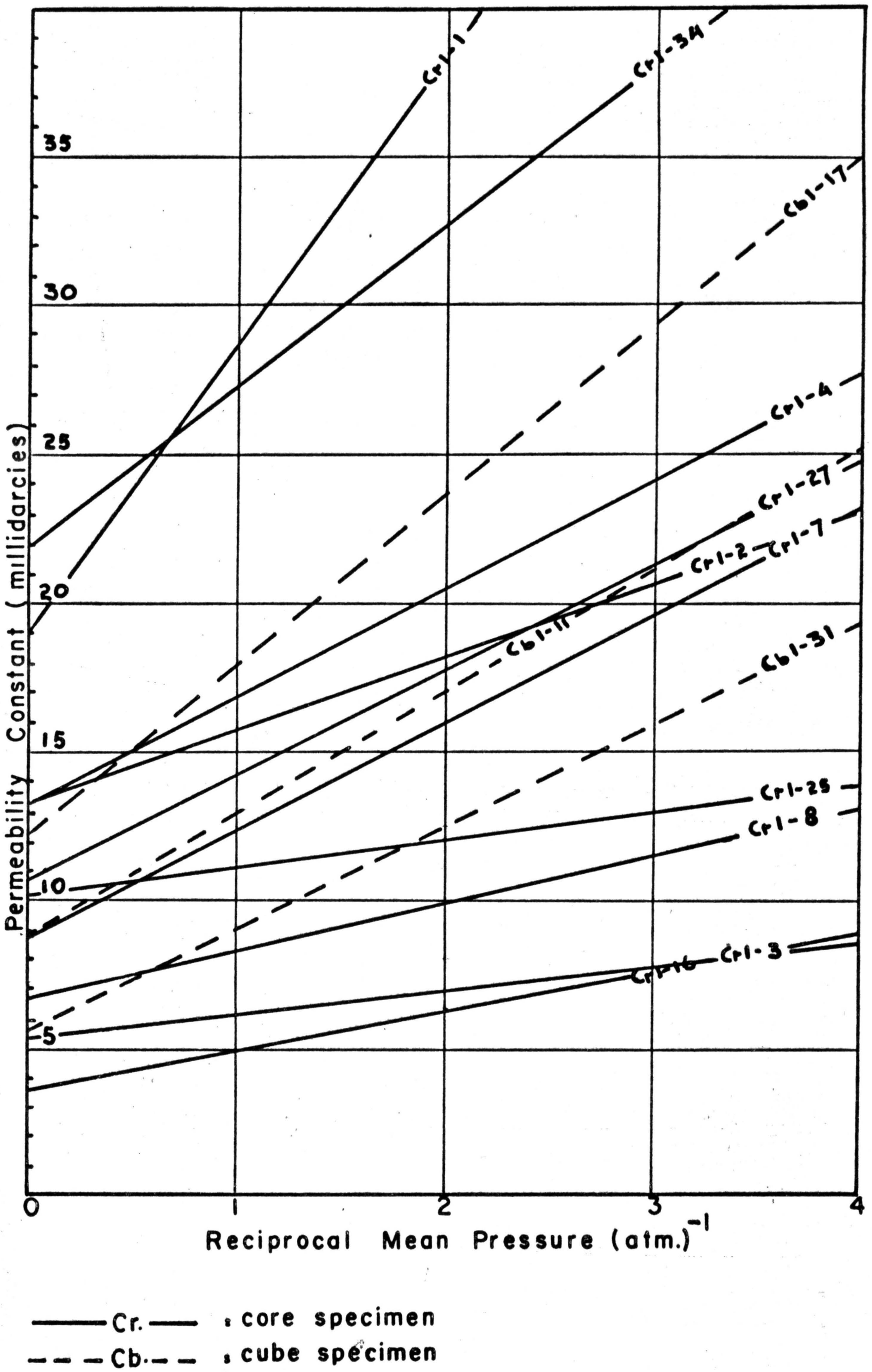

Fig. 10. Curves of Apparent Permeability Versus Reciprocal Mean Pressure of One Inch Specimens, as Obtained from the Data in Table I.

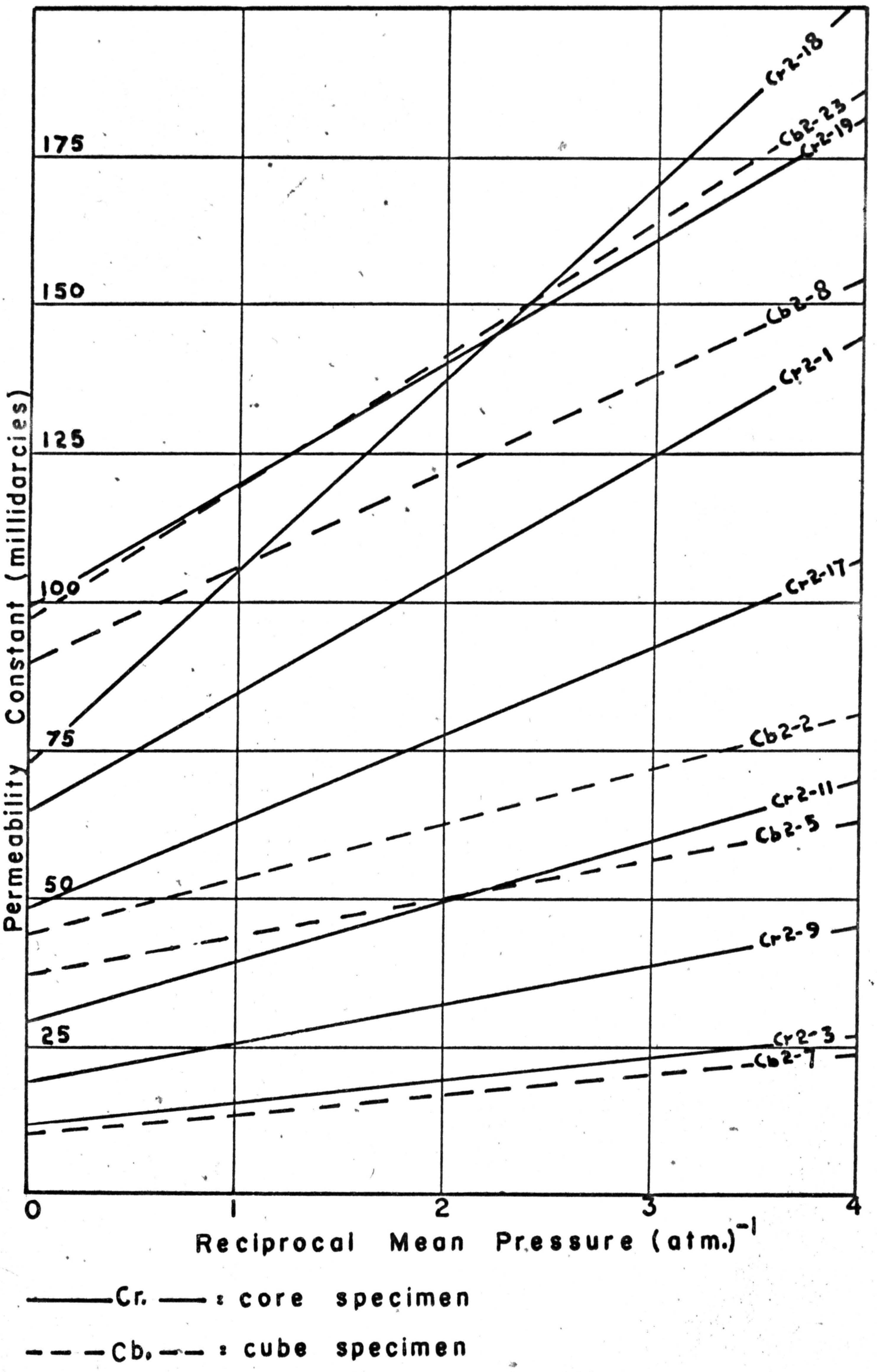

Fig. 11. Curves of Apparent Permeability Versus Reciprocal Mean Pressure of Two Inch Specimens, as Obtained from the Data in Table I.

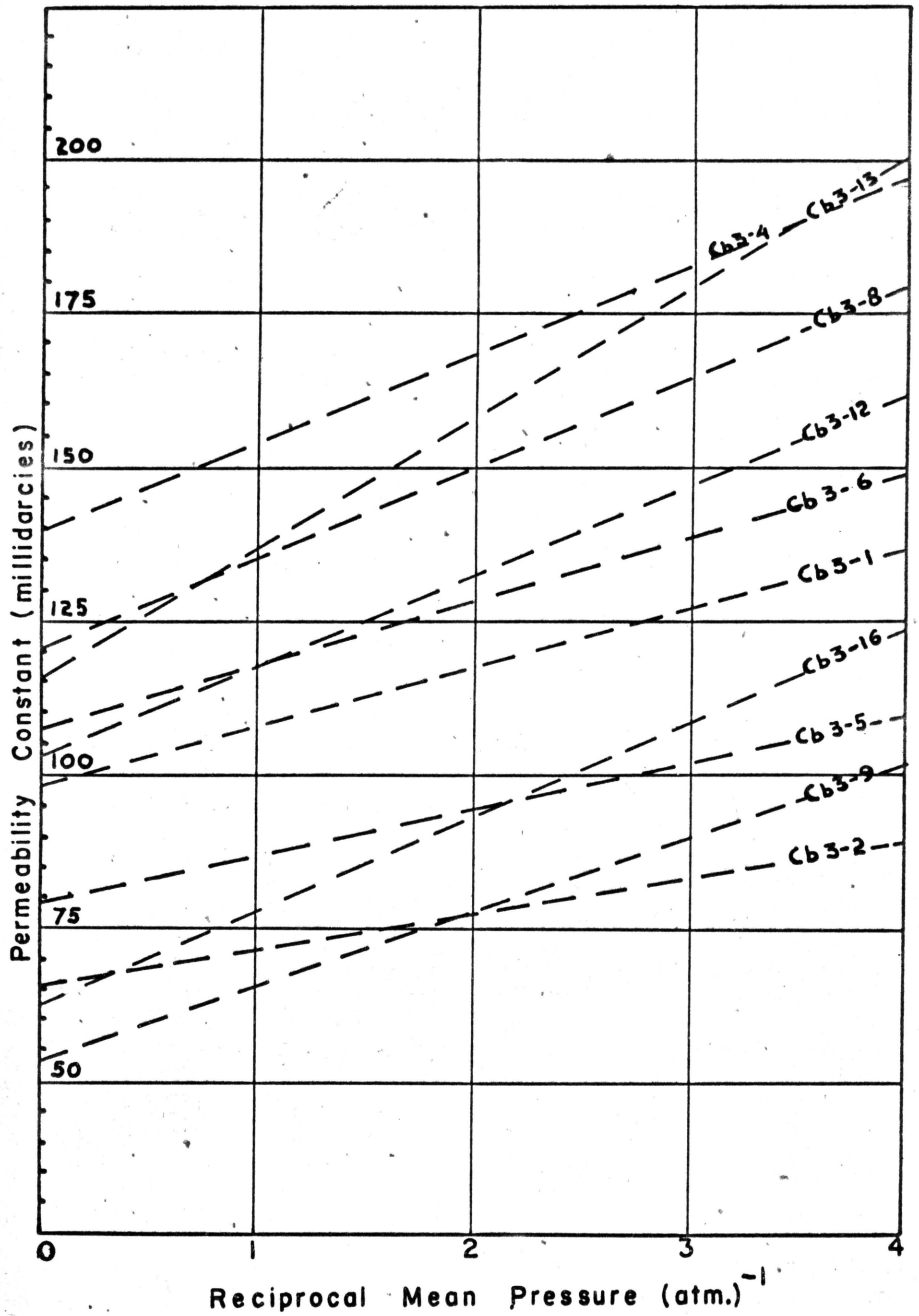

Fig. 12. Curves of Apparent Permeability Versus Reciprocal Mean Pressure of Three Inch Specimens, as Obtained from the Data in Table I.

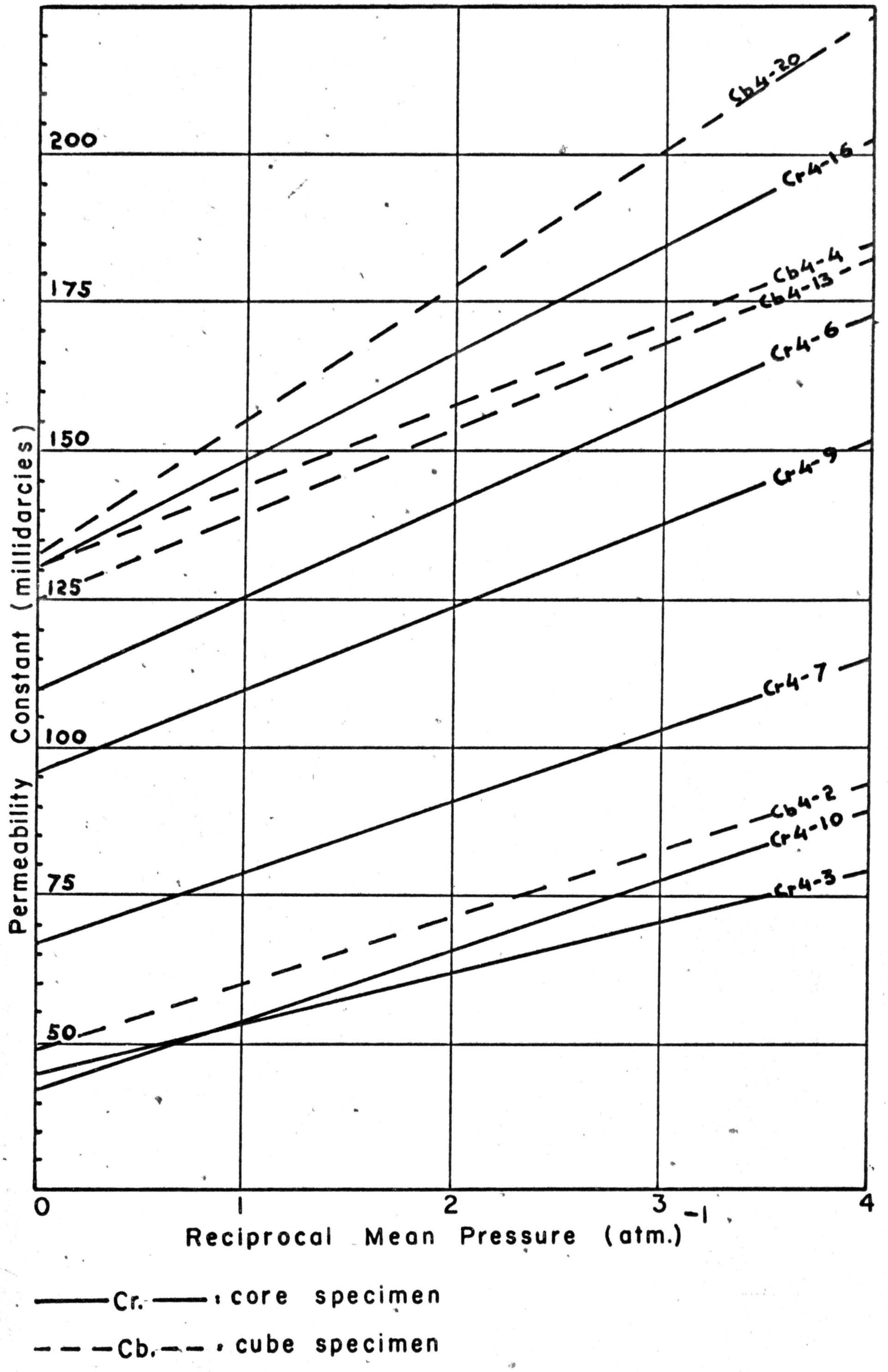

Fig. 13. Curves of Apparent Permeability Versus Reciprocal Mean Pressure of Four Inch Specimens, as Obtained from the Data in Table I.

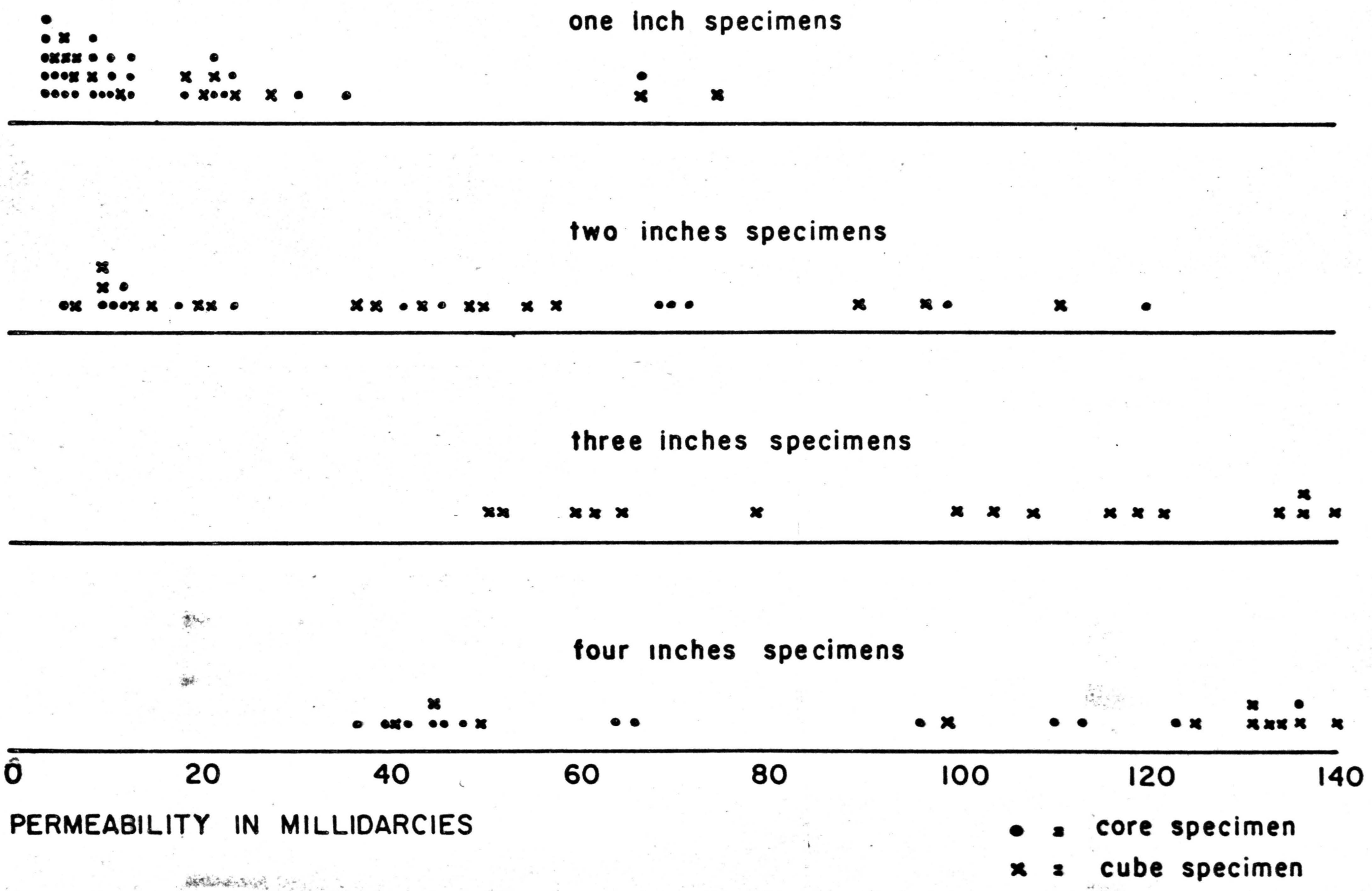

Fig. 14. Frequency Distribution Diagram of Permeability

V. ANALYSIS OF RESULTS

The purpose of the analysis is:

1. To find the linear relationship between specimen size and permeability value from a scatter diagram shown in Figure 15 which was obtained from the data in Table 1.
2. To make comparisons between the average permeability values of different shapes and sizes of specimens by using analysis of variance method. These comparisons were made to find the effect of geometrical shape and to find the representative size of specimen for coal permeability test.

Regression Method

The relationship between specimen size and permeability value will fit the model $Y = b X + a$, when Y is the permeability in millidarcies and X is the size in inches. The following computations were made based on the values shown in Table 8 of Appendix C, and the formula shown in Appendix D.

(i) $$\sum_{i=1}^{N} X_i Y_i = 1\sum_{i=1}^{n_1} Y_{1i} + 2\sum_{i=1}^{n_2} Y_{2i} + 3\sum_{i=1}^{n_3} Y_{3i} + 4\sum_{i=1}^{n_4} Y_{4i}$$

$$= 1\,T_1 + 2\,T_2 + 3\,T_3 + 4\,T_4 = 16674.70$$

(ii) $$\frac{\left(\sum_{i=1}^{N} X_i\right)\left(\sum_{i=1}^{N} Y_i\right)}{N} = \frac{(1\,n_1 + 2\,n_2 + 3\,n_3 + 4\,n_4)\,T}{N}$$

$$= \frac{248\ T}{113} = 12644.00$$

(iii) $\sum_{i=1}^{N} X_i^2 = n_1(1) + n_2(4) + n_3(9) + n_4(16)$

$$= 42 + 124 + 144 + 384 = 694$$

(iv) $S\,S_{XY} = \sum_{i=1}^{N} X_i Y_i - \frac{(\sum_{i=1}^{N} X_i)\ (\sum_{i=1}^{N} Y_i)}{N}$

$$= 16674.70 - 12644.00 = 4030.70$$

(v) $S\,S_X = \sum_{i=1}^{N} X_i^2 - \frac{(1n_1 + 2n_2 + 3n_3 + 4n_4)^2}{N}$

$$= 149.72$$

(vi) $\overline{Y} = \frac{T}{N} = \frac{5761.20}{113} = 50.98$

$$\overline{X} = \frac{42(1) + 31(2) + 16(3) + 24(4)}{113}$$

$$= 2.19$$

$$b = \frac{S\,S_{XY}}{S\,S_X} = 26.92$$

$$a = \overline{Y} - b\,\overline{X} = 50.98 - (26.92)(2.19)$$

$$= -\ 7.97$$

The relationship between Y and X from the scatter diagram shown in Figure 15 is:

$$Y = 26.9\,X - 7.9$$

Analysis of Variance

The analysis by the regression method showed that the

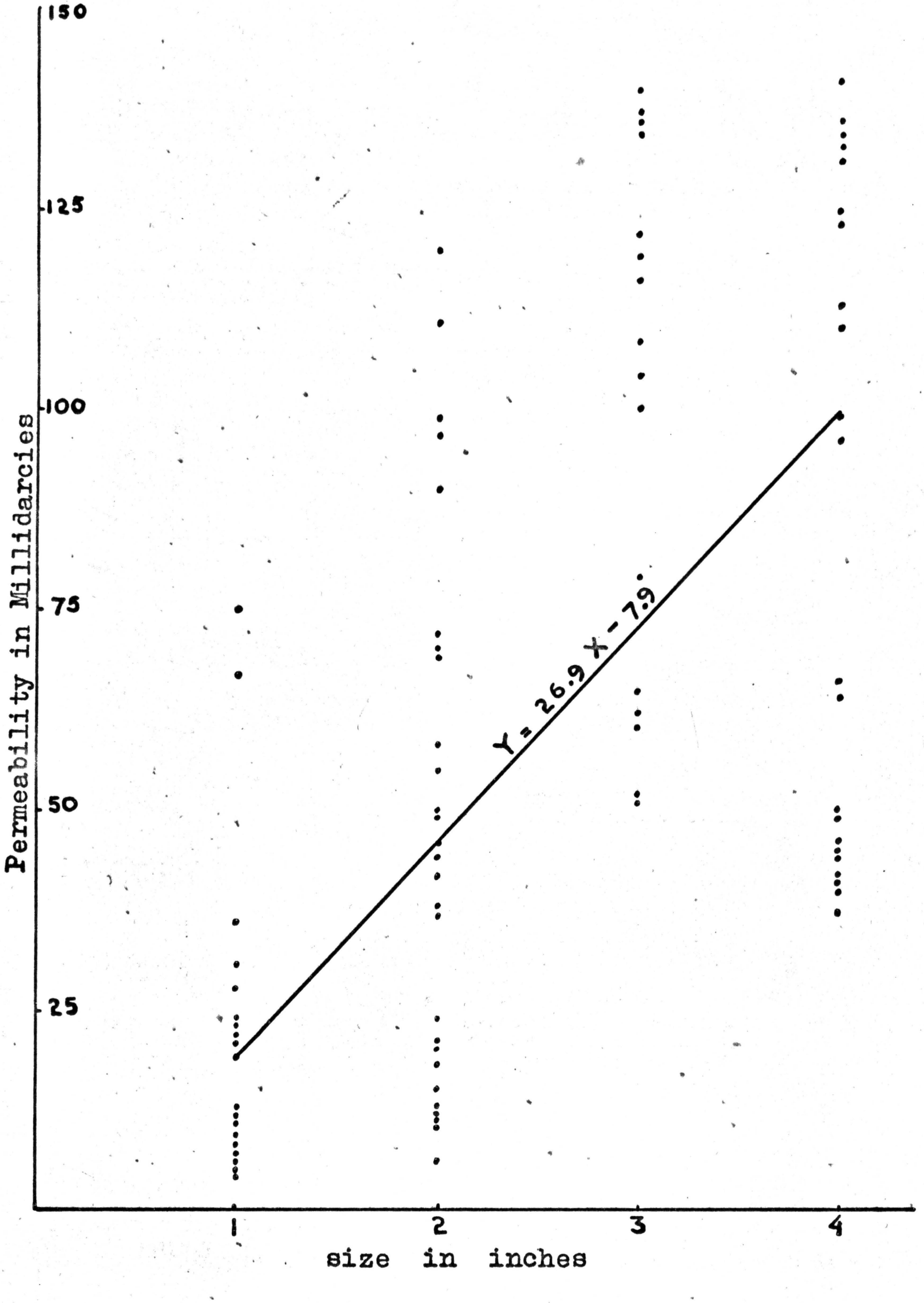

Fig. 15. Relationship Between
Specimen Size and Permeability
Value from a Scatter Diagram

permeability values increased with an increase of size, as shown by equation $Y = 26.9 X - 7.9$. The analysis of variance was used to make comparisons between the average permeability values of different shapes and sizes; to see how significantly the permeability values differ due to the change of size and shape.

The following comparisons were made :

1. Comparisons Between Shapes:

   C_1, comparison between shapes of one-inch specimens.

   C_2, comparison between shapes of two-inch specimens.

   C_3, comparison between shapes of four-inch specimens.

2. Comparisons Between Sizes:

   The comparisons were made based on the Table of Values of Orthogonal Coefficients for Comparison of Treatments, as shown in Appendix C, Table 8.

   C_4, comparison between sizes one inch versus two inch.

   C_5, comparison between sizes (1 & 2) versus (3 & 4).

   C_6, comparison between sizes three inch versus four inch.

   C_7, comparison between sizes two inch versus four inch.

   C_8, comparison between sizes one inch versus four inch.

   C_9, comparison between sizes (1 & 4) versus (2 & 3).

   C_{10}, comparison between sizes one inch versus three inch.

C_{11}, comparison between sizes two inch versus four inch.

C_{12}, comparison between sizes (1 & 3) versus (2 & 4).

Comparisons Between Shapes (see values in Appendix C)

For one inch specimens:

(i) Total Sum of Squares = T S S

$$T\,S\,S = (Y^2_{core\ 1} + \ldots + Y^2_{core\ 28} + Y^2_{cube\ 1} + \ldots + Y^2_{cube\ 14}) - \frac{(T_{core} + T_{cube})^2}{n_{core} + n_{cube}} = 12143.97$$

(ii) Between Shapes Sum of Squares = B S S

$$B\,S\,S = \frac{T^2_{core}}{n_{core}} + \frac{T^2_{cube}}{n_{cube}} - \frac{(T_{core} + T_{cube})^2}{n_{core} + n_{cube}} = 611.28$$

(iii) Error Sum of Squares = E S S

$$E\,S\,S = T\,S\,S - B\,S\,S = 11532.69$$

The same method of computations were used for the two-inch specimens and four-inch specimens, and a table was constructed by picking the proper quantities from the computation (Table 2).

Comparisons Between Sizes (see values in Appendix C)

(i) Correction Term = C T

$$C\,T = \frac{T^2}{N} = 293729.42$$

(ii) $$T\,S\,S = (Y^2_{1-1} + \ldots + Y^2_{1-42} + Y^2_{2-1} + \ldots + Y^2_{2-31} + Y^2_{3-1} + \ldots + Y^2_{3-16} + Y^2_{4-1} + \ldots + Y^2_{4-24}) - C\,T = 223035.93$$

TABLE 2. ANALYSIS OF VARIANCE TABLE FOR COMPARISONS BETWEEN SHAPES

	SOURCE OF VARIATION (S.V.)	DEGREES OF FREEDOM (D.F.)	SUM OF SQUARES (S.S.)	MEAN SQUARES (M.S. = $\frac{SS}{DF}$)	F-VALUE $F = \frac{MSB}{MSE}$	F-TABULAR	
						5%	1%
One-Inch Specimen	Between Shapes	1	611.28	611.28	2.12	4.08	7.31
	Error	40	11532.69	288.31	----	----	----
Two-Inch Specimen	Between Shapes	1	10.09	10.09	0.01	4.18	7.60
	Error	29	34206.23	1179.52	----	----	----
Four-Inch Specimen	Between Shapes	1	3626.68	3626.68	0.43	4.35	8.10
	Error	22	186157.05	8461.68	----	----	----

(iii) Between Size Sum of Squares = B S S

$$B\ S\ S = \left(\frac{T_1^2}{n_1} + \frac{T_2^2}{n_2} + \frac{T_3^2}{n_3} + \frac{T_4^2}{n_4}\right) - C.T.$$

$$= 122854.45$$

(iv) Error Sum of Squares = E S S

$$E\ S\ S = T\ S\ S - B\ S\ S$$

$$= 100181.48$$

(v) Comparison 4, C_4

$$S\ S\ C_4 = \frac{T_1^2}{n_1} + \frac{T_2^2}{n_2} - \frac{(T_1 + T_2)^2}{n_1 + n_2}$$

$$= 12466.83$$

Comparison 5, C_5

$$S\ S\ C_5 = \frac{(T_1 + T_2)^2}{n_1 + n_2} + \frac{(T_3 + T_4)^2}{n_3 + n_4} - \frac{T^2}{N}$$

$$= 109383.93$$

Comparison 6, C_6

$$S\ S\ C_6 = \frac{T_3^2}{n_3} + \frac{T_4^2}{n_4} - \frac{(T_3 + T_4)^2}{n_3 + n_4}$$

$$= 1003.69$$

(vi) The following Table 3 was then constructed by picking the proper quantities from above computations.

(vii) Using the same method, Table 4 was constructed.

TABLE 3. ANALYSIS OF VARIANCE TABLE FOR COMPARISONS BETWEEN SIZES

SOURCE OF VARIATION (S.V.)	DEGREES OF FREEDOM (D.F.)	SUM OF SQUARES (S.S.)	MEAN SQUARES (M.S. = $\frac{SS}{DF}$)	F-Value $F = \frac{MSB}{MSE}$	F-Tabular	
					5%	1%
Between Sizes	3	122854.45	40951.48	44.50	2.69	3.96
Comparison C_4	1	12466.83	12466.83	13.56	3.93	6.90
Comparison C_5	1	109383.93	109383.93	119.01	3.93	6.90
Comparison C_6	1	1003.69	1003.69	1.09	3.93	6.90
Error	109	100181.48	919.09 = MSE	------	----	----

TABLE 4. ANALYSIS OF VARIANCE TABLE FOR COMPARISONS BETWEEN SIZES

S.V.	D.F.	S.S.	M.S.	F-VALUE	F-TABULAR	
					5%	1%
Comparison C_7	1	33077.65	33077.65	35.98	3.93	6.90
Comparison C_8	1	125619.94	125619.94	136.67	3.93	6.90
Comparison C_9	1	10165.14	10165.14	11.06	3.93	6.90
Comparison C_{10}	1	78713.04	78713.04	85.64	3.93	6.90
Comparison C_{11}	1	28326.46	28326.46	30.82	3.93	6.90
Comparison C_{12}	1	15814.95	15814.95	17.21	3.93	6.90

TABLE 5. MEANS ($\overline{Y}$), STANDARD DEVIATIONS (s), COEFFICIENTS OF VARIATION (c.v.) FOR PERMEABILITY VALUES OF DIFFERENT SIZES.*)

Size (inches)	Means (Y, in millidarcies)	Standard Deviation (s, in millidarcies	Coefficients of Variation. c.v. %
1	16.73	17.21	102.87
2	43.16	33.76	78.22
3	99.15	32.64	32.92
4	88.92	40.55	45.60

Conclusions from the Analysis

1. Comparisons between shapes showed that there is insignificant difference in the permeability by using two different geometrical shapes: cylindrical and rectangular specimens.
2. Comparison between sizes of 113 coal specimens showed that there are significant differences in the average permeability of the four sizes **).

---

*) For computations, see Appendix C.

**) The comparisons are made with 5% point for the distribution of F.

3. There is significant difference between results in one- and two-inch specimens.
4. Both comparisons between one-inch versus three-inch specimens and one-inch versus four-inch specimens showed significant differences.
5 Comparison between two-inch and three-inch specimens showed significant differences.
6. Comparisons between three-inch and four-inch specimens showed insignificant difference of the permeability values, and the three-inch specimen had the least value of coefficient of variation.

Statistical Analysis by Computer

By using Program BMD03R, Multiple Regression With Case Combinations, which is available in the Computing Center of Virginia Polytechnic Institute, the statistical analysis of the data has been carried out. Seven comparisons, as shown in Appendix E, were selected. All results are in agreement with the previous results of the analysis.

VI. DISCUSSION OF RESULTS

A. Effect of Gas Slippage Phenomena

One of the objects of this investigation was to determine the extent to which the gas-slippage effect may occur in laboratory tests for permeability on coal specimens. Numerous investigators [1,2,3,4] have noted the existence of the gas slippage phenomena in permeability measurements using air as a fluid. With the work of these investigators as a background, experiments were performed on the flow of air through coal specimens.

As a result of the gas-slippage effect, the apparent or observed permeabilities to gas are greater than the true values. This is due to the absence of a stationary layer of gas in contact with the walls of the flow channels, as verified by Fulton.[2] However, a reduction in gas permeability can also be due to turbulence.[22] In this connection, therefore, it is very important to make sure that the permeability measurements are carried out under laminar flow conditions for gas.

The measurements of coal permeability provided results which are in accord with Klinkenberg's concept that permeabilities as ordinarily measured using air, vary according to the mean pressure used in the measurements. Table 1 showed that the higher the mean pressure used, the lower the calculated value of this permeability. The apparent permeability k_a extrapolated to infinite pressure, or $\frac{1}{P} = 0$, should give the true permeability.

Constant b by definition measures the magnitude of the slip correction which must be applied in a given instance. As b is inversely proportional to the radius of the capillaries r, the value of b may be expected to be small for highly permeable samples and to be larger for less permeable samples.[3] The results of experiments, as shown in Table 1, are in general agreement with this concept. There are some deviations shown in the results of the one-inch specimens.

The data in Table 1 showed also that the value of the observed permeability is always larger than the true permeability by 25 to 150 per cent. The percentage differences are considerable, although the absolute discrepancies may be small, so that in these cases it is advisable to take into account the gas slippage phenomena. As a consequence, to properly compare the permeability values of different specimen sizes, correction for gas slippage should first be made.

B. Effect of Geometrical Shape

The practice of permeability measurement in the petroleum industry showed that the sample used for the measurement can be either of a cylindrical or rectangular form. Previous coal permeability tests were conducted with cube specimens.[6,8,9] For practical purposes there are some advantages to use core or cylindrical specimens. It was one of the objects of this investigation to determine the effect of geometrical shape of the specimen on the permeability value. Comparisons were made for cylindrical specimens of one inch, two inch, and four inch diameters versus the corresponding dimensions of the cube specimens. Data given in Figure 14 shows that the permeability values of both shapes of specimens are equally distributed. The results of the statistical analysis, as shown in Table 2, indicates that there is an insignificant difference in the average permeability value between cylindrical specimens and rectangular specimens of the same size. These were indicated by the smaller value of F-computed as compared with F-tabular. It can be concluded that the geometrical shape of the specimen has no significant effect on the coal permeability value. It is only a matter of practical convenience whether to use the cylindrical or rectangular specimen.

The cylindrical shape has the following advantages for practical purposes:

1. Samples can be obtained from exploration core drilling, which enables permeability tests to be included as part of the core analysis to learn the character of the coal seam.
2. It is also possible to design a portable core drilling machine to take samples directly from coal face for permeability testing.
3. More uniform and precise geometrical dimensions of specimens can be obtained.

C. Effect of Geometrical Dimension

It was determined that there is no effect of coal specimen shape on the permeability value, so that for the study of the effect of the geometrical dimensions of the specimen both shapes can be used to represent the same size. The analysis of results from the scatter diagram showed that permeability of coal increases with the increase of size as shown by the linear relationship $Y = 26.9 X - 7.9$. This is due to the heterogeneous character of coal, wherein the number of fractures found in a smaller specimen per unit area is not the same as in the bigger ones. It can be understood that the bigger the sample, the better it will represent a coal seam's characteristic permeability value. However,from a practical point of view, it is not as convenient to handle the larger sizes of specimen. It was one of the purposes of this investigation to find the representative size of specimen, beyond which there was no more effect of specimen size.

It has been mentioned before that in one coal seam there can be different kinds of coal such as vitrain, clarain, durain, and fusain which are physically different from each other. Besides, it is not uncommon to have layers of rock in a coal seam. This is the reason why the range of permeability values of the smaller sizes (the one inch- and two inch-specimens) is larger than the bigger ones. Theoretically, for a homogeneous material, the permeability value will be the same regardless of specimen size. For coal it is difficult to prepare a sample of small size which has a high permeability value, due to its brittleness. Another factor which apparently also affects the permeability value for different sizes of specimens is the occurrence of cleavage planes which are found in coal seams. The angle of the cleavage and the distance between each successive plane will give an effect to the number of cleavage planes per unit volume of different sizes of specimen as shown in Figure 16.

The analysis of variance in Table 3 shows that there are significant differences in the average permeability values between sizes. The analysis shows that there is an insignificant difference between the permeability values of the specimens of sizes three inches and four inches. Table 5 of the analysis shows also that the specimens of three inches have the least coefficient of variation value. From the aforementioned analysis, it can be concluded that the three-inch specimen is the representative size of sample for coal. It means that beyond the three inch size the permeability value of the coal may be the same regardless of its size. Due to the heterogeneous character of coal seam however, it is a matter of sampling of the seam to get the representative permeability value of the coal seam.

D. Remarks on the Experiment

The coal sample was taken from the mine without the use of any explosive to avoid additional fractures in the

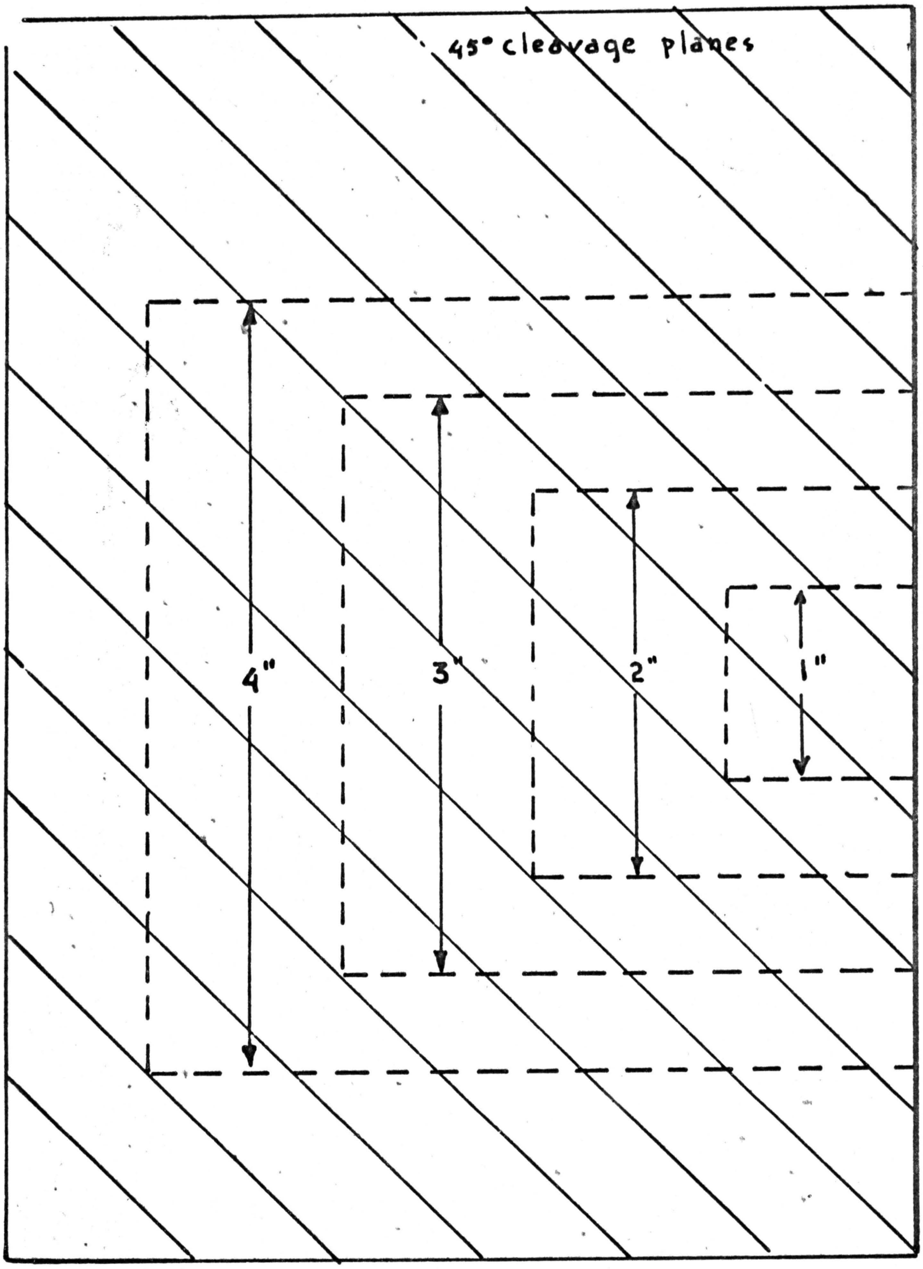

Fig. 16 . Diagram Showing the Relation of Cleavage Planes and Specimen Size

sample. From the 33.5 inch-thick block of the biggest coal sample shown in Figure 17, different layers can be easily distinguished. The result of permeability measurements of four different sizes shows that the average permeability values of the top and bottom sections of the seam are higher than the middle section as shown in Table 6. This apparently is due to the occurrence of more fractures in the upper and lower parts of the seam which in turn is caused by different kinds of coal composition with different physical properties. Proximate analysis of the three sections shown in Appendix B shows that the middle section has a high ash content which is derived from the thick layer of slate.

From the measurements it appeared also that the bedding planes between rock and coal might become a good flow passage for gas if there is any displacement due to pressure caused by mining operations. To make better permeability measurements using air as a fluid, the apparatus should be provided with a more accurate control for flow and pressure readings. It will then be possible to obtain more observed permeability values under different pressures. These improvements would provide a means for an improved extrapolation for true permeability values. All the computations can be done by the digital computer by using the programs shown in Appendix A.

TABLE 6. PERMEABILITY VALUES OF TOP -, MIDDLE -, AND BOTTOM-SECTION OF SAMPLE

ONE-INCH SPECIMENS					
TOP		MIDDLE		BOTTOM	
SAMPLE	K_L	SAMPLE	K_L	SAMPLE	K_L
Cr 1-3	5.87	Cr 1-4	13.09	Cr 1-1	18.84
Cr 1-5	4.99	Cb 1-11	8.90	Cr 1-2	13.38
Cr 1-7	8.86	Cb 1-17	12.11	Cr 1-6	6.03
Cr 1-8	6.77	Cr 1-19	3.68	Cr 1-14	11.22
Cr 1-10	23.55	Cb 1-22	7.26	Cr 1-16	3.63
Cr 1-12	5.37	Cr 1-26	13.32	Cb 1-21	18.79
Cr 1-13	3.77	Cb 1-30	7.62	Cr 1-24	9.40
Cr 1-15	21.64	Cr 1-33	4.14	Cb 1-23	21.38
Cr 1-18	24.55	Cb 1-35	6.13	Cb 1-32	22.23
Cr 1-20	11.01	Cr 1-38	30.99	Cb 1-36	4.98
Cr 1-25	10.32	Cr 1-39	35.76	Cr 1-40	66.94
Cr 1-27	10.74			Cb 1-42	28.40
Cr 1-28	4.33				
Cb 1-9	24.35				
Cr 1-29	9.31				
Cr 1-31	5.68				
Cr 1-34	21.75				
Cb 1-37	66.72				
Cb 1-41	75.18				
$\bar{K}_L$ TOP= 18.14		$\bar{K}_L$ MID = 13.00		$\bar{K}_L$ BOT = 18.77	

TABLE 6.
(Cont'd)

TWO-INCH SPECIMENS					
TOP		MIDDLE		BOTTOM	
SAMPLE	K_L	SAMPLE	K_L	SAMPLE	K_L
Cr 2-1	69.01	Cr 2-9	18.57	Cr 2-3	12.10
Cb 2-2	44.08	Cr 2-11	24.07	Cb 2-5	37.05
Cr 2-4	42.00	Cb 2-7	10.34	Cr 2-10	10.81
Cr 2-6	11.94	Cr 2-12	5.87	Cr 2-13	7.07
Cb 2-8	90.10	Cr 2-19	99.35	Cb 2-14	9.77
Cr 2-15	70.55	Cb 2-27	20.08	Cr 2-16	10.15
Cr 2-17	46.23	Cb 2-28	14.74	Cr 2-18	72.30
Cr 2-20	120.29			Cb 2-23	96.67
Cb 2-21	13.38			Cb 2-30	38.03
Cb 2-22	20.60			Cb 2-31	58.43
Cb 2-24	54.68				
Cb 2-26	48.60				
Cb 2-25	50.46				
Cb 2-29	110.90				
$\overline{K}_L$ TOP =	56.63	$\overline{K}_L$ MID=	27.57	$\overline{K}_L$ BOT =	35.24

TABLE 6.
(Cont'd)

THREE-INCH SPECIMENS					
TOP		MIDDLE		BOTTOM	
SAMPLE	K_L	SAMPLE	K_L	SAMPLE	K_L
Cb 3-4	139.89	Cb 3-1	100.17	Cb 3-2	65.40
Cb 3-5	78.81	Cb 3-7	59.63	Cb 3-3	135.97
Cb 3-6	108.57	Cb 3-12	103.69	Cb 3-9	52.44
Cb 3-8	121.96	Cb 3-15	50.78	Cb 3-10	119.41
Cb 3-11	137.01	Cb 3-16	62.49	Cb 3-13	115.64
Cb 3-14	134.55				
$\bar{K}_L$ TOP = 120.13		$\bar{K}_L$ MID = 75.35		$\bar{K}_L$ BOT = 97.77	
FOUR-INCH SPECIMENS					
Cr 4-1	135.76	Cr 4-3	45.30	Cr 4-7	66.57
Cb 4-2	49.89	Cr 4-8	63.99	Cr 4-9	96.01
Cb 4-4	132.89	Cr 4-16	131.47	Cr 4-12	40.24
Cr 4-5	48.58	Cb 4-22	40.97	Cr 4-15	113.03
Cr 4-6	110.42	Cb 4-23	44.44	Cr 4-17	122.72
Cr 4-10	41.94	Cb 4-24	99.26	Cb 4-20	136.22
Cr 4-11	37.25				
Cr 4-13	124.95				
Cr 4-14	46.38				
Cb 4-18	134.25				
Cb 4-19	131.24				
Cb 4-21	140.60				
$\bar{K}_L$ TOP = 94.52		$\bar{K}_L$ MID = 70.90		$\bar{K}_L$ BOT = 95.79	

VII. CONCLUSIONS

From a study of the results of the experiments on coal permeability to gas flow, the following conclusions can be drawn:

1. As a result of the gas slippage effect, the observed coal permeability to gas is greater than the true value. The percentage difference is considerable, so that in coal permeability measurements using air as a fluid, the effect of gas slippage should be taken into account and corrections should be made. The observed permeability k_a extrapolated to infinite pressure should give the true permeability k_L . The value of k_L can be found either graphically or mathematically.
2. The geometrical shape of the specimen has no effect on the permeability value. The use of a cylindrical specimen is preferable for practical reasons, such as the possibility of performing the permeability measurements on core-drill samples.
3. The permeability value of coal increases with an increase in specimen size, probably because more fractures per unit volume are found in the bigger samples.
4. The statistical analysis showed that specimen sizes of

three inches can be considered as the representative size for coal permeability for the coal tested. Due to the heterogeneous character of coal, however, it is very important to emphasize the importance of the sampling method of the coal seam to get a representative permeability value of the seam.

5. Permeability values reflect directly a characteristic of the coal as it exists underground. It is therefore important to establish interrelationships between the petrographic peculiarities of the different coal varieties and their permeability values.
6. Using the results of permeability measurements on three-inch specimens, the coal permeability value of the seam under consideration in this study would be 99.15 millidarcies which is the mean value of the three-inch specimens. Higher permeability values are found in the top and bottom portions of the seam.

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APPENDIX A

FORTRAN SOURCE LIST

PERMEABILITY ANALYSIS

```
      DIMENSION Q(10), P(10), T(2,3), KA(10), KAA(10)
      DIMENSION PC(10)
      REAL L, KA, KAA
      LOGICAL LG
C     PRINT PAGE HEADINGS
    1 WRITE (6,200)
      WRITE (6,201)
      WRITE (6,202)
      N2 = 3
    2 N = 1
      T(1,3) = 0.
      T(2,1) = 0.
      T(2,2) = 0.
      T(2,3) = 0.
C     READ MAIN DATA CARD OF EACH SAMPLE
      READ(5,100) LG,ANAM1, ANAM2, U, L, A, P(N), Q(N)
  100 FORMAT(L1, 2A6, F6.5, F5.3, F5.3, F3.2, F4.2)
C     BLANK CARD WILL END CALCULATIONS
      IF(Q(N).EQ.0.0 .AND. P(N).EQ.0.0) GO TO 99
      GO TO 4
    3 N = N+1
C     READ DATA CARDS WITH VARYING PRESSURES AND QUANTITIES
      READ (5,101) LG, P(N), Q(N)
  101 FORMAT(L1,28X, F3.2, F4.2)
    4 KA(N) = 1000.*U*L*Q(N)/(A*P(N))
      C = A
C     SUM TOTALS AND STORE IN MATRIX
      T(1,3) = T(1,3) + KA(N)
      T(2,1) = T(2,1) + 1.0/P(N)
```

APPENDIX A
(Cont'd)

```
      T(2,2) = T(2,2) + 1.0/(P(N)*P(N))
      T(2,3) = T(2,3) + KA(N)/P(N)
      IF (.NOT.LG) GO TO 3
      T(1,1) = N
      T(1,2) = T(2,1)
C     SOLVE SIMULTANEOUS EQUATIONS FOR LEAST SQUARES REGRESSION LINE
      DO 10 J=1,2
      T1 = T(J,1)
      DO 11 K=1,3
   11 T(J,K) = T(J,K)/T1
   10 CONTINUE
      DO 12 K=1,3
   12 T(2,K) = T(2,K) - T(1,K)
      B = T(2,3)/T(2,2)
      A = T(1,3) - B*T(1,2)
      B = B/A
      SOLVE FOR PERCENT DIFFERENCE OF ACTUAL VS PREDICTED VALUES OF P AND Q
      DO 15 J=1,N
      KAA(J) = A*(1. + B/P(J))
      PC(J) = (KAA(J) - KA(J))/KA(J)*100.
   15 CONTINUE
C     WRITE RESULTS
      J = 1
      WRITE(6,203)ANAM1,ANAM2,L,C,P(J),Q(J),KA(J),A,B,KAA(J),PC(J)
      N2 = N2 + 1
   18 J = J + 1
      WRITE(6,204) P(J),Q(J),KA(J),KAA(J),PC(J)
      N2 = N2 + 1
      IF(J.LT.N) GO TO 18
```

APPENDIX A
(Cont'd)

```
C       CHECK TO SEE IF PAGE IS FILLED
        IF (18.GT.N2) GO TO 2
        GO TO 1
  200 FORMAT(1H1//// 9X, 6HSAMPLE, 6X, 6HLENGTH, 2X, 5HCROSS, 2X,
     18HPRESSURE, 9HFLOWRATE, 2X, 12HPERMEABILITY, 9X, 9HPREDICTED, 5X,
     27HPERCENT)
  201 FORMAT(1H+,8X,6HNUMBER,7X,4H(CM),2X,7HSECTION,2X,6H(ATMS),2X,
     18H(CC/SEC),1X,14H(MILLIDARCIES),4X,1HB,4X,8HAPPARENT,4X,
     210HDIFFERENCE)
  202 FORMAT(1H+,27X,7H(SQ CM),19X,8HAPPARENT,2X,4HTRUE,7X,
     112HPERMEABILITY)
  203 FORMAT(1HO,6X,2A6,2F8.3,F7.2,4X,F5.2,3X,F7.3,F7.2,F7.3,2X,F7.3,5X,
     1F7.2)
  204 FORMAT(1HO,34X,F7.2,4X,F5.2,3X,F7.3,16X,F7.3,5X,F7.2)
   99 STOP
      END
```

APPENDIX B

DESCRIPTION OF COAL SAMPLE

Origin of coal sample: Pocahontas No. 3 seam, from Itmann No. 3 Mine, with 500 ft. overburden and approximately 800 ft. from the outcrop.

Typical stratification of the seam at the section where the sample was taken:

roof : sandy shale

coal	9.25	inches
rock/slate	2.75	"
fusain coal	2.00	"
bone	2.50	"
coal	2.00	"
fusain coal	0.25	"
coal	13.00	"
bone	4.00	"
coal	13.00	"

floor: sandy shale

Dimensions of the biggest block of sample, shown in Figure 17 are:

height/thickness	33.50	inches
length	48.00	"
width	28.00	"

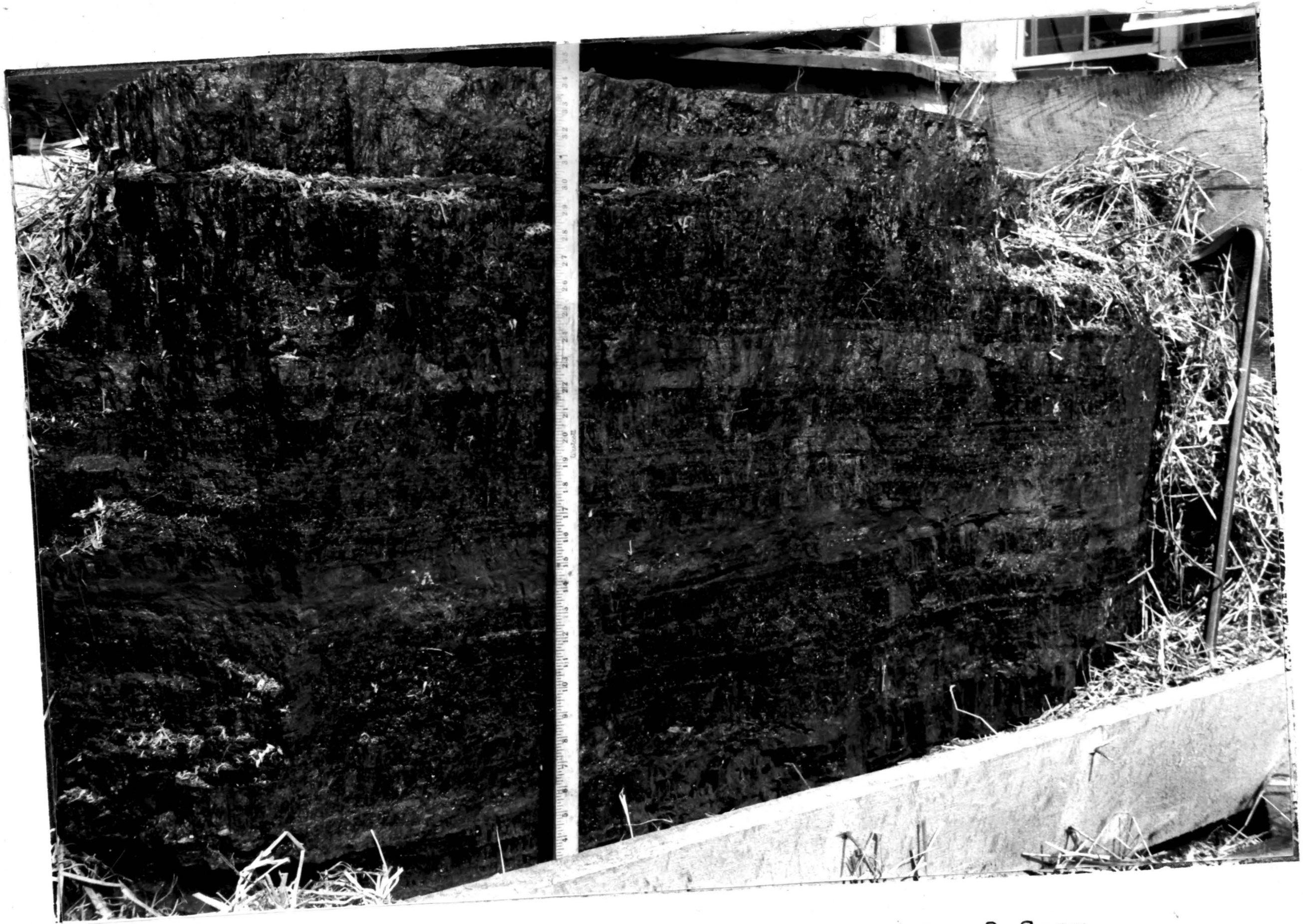

Fig. 17. Gross Sample of Pocahontas No. 3 Seam from Itmann No. 3 Mine

The sample was divided into three sections, and treated separately for the permeability tests:

Top coal: the first 12.30 inches from top, including two inches of slate.

Middle coal: middle part of the coal block, 8.7 inches thick, including 2.2 inches of slate.

Bottom coal: the rest of the lower part of the sample, which is 12.5 inches of coal.

TABLE 7. PROXIMATE ANALYSIS OF THE COAL SAMPLE

	Ash Content* %	Vol. Matter %	Fixed Carbon %	Sulphur %
Composite	15.177	18.731	66.092	1.022
Top Coal	14.688	16.598	68.714	
Middle Coal	16.063	19.627	64.310	
Bottom Coal	5.706	20.205	74.089	

*All values are on moisture-free basis.

APPENDIX C

TABLE 8. ACTUAL DATA OF PERMEABILITY VALUES

ONE-INCH SPECIMENS				TWO-INCH SPECIMENS			
CORE		CUBE		CORE		CUBE	
Y	Y^2	Y	Y^2	Y	Y^2	Y	Y^2
18.8	353.44	24.3	590.49	69.0	4761.00	44.1	194.81
13.4	179.56	8.9	79.21	12.1	146.41	37.0	1369.00
5.9	34.81	12.1	146.41	42.0	1764.00	10.3	106.09
13.1	171.61	18.8	353.44	11.9	141.61	90.1	8118.01
5.0	25.00	7.3	53.29	18.6	345.96	7.1	50.41
6.0	36.00	21.4	457.96	10.8	116.64	9.8	96.04
8.9	79.21	7.6	57.76	24.1	580.81	13.4	179.56
6.7	44.89	5.7	32.49	5.9	34.81	20.6	424.36
23.5	552.25	22.2	492.84	70.5	4970.25	96.7	9350.89
5.4	29.16	6.1	37.21	10.1	102.01	54.7	2992.09
3.7	14.21	5.0	25.00	46.2	2134.44	50.5	2550.25
11.2	125.44	66.7	4448.89	72.3	5227.29	48.6	2361.96
21.6	466.54	75.2	5655.04	99.3	9860.49	20.1	404.01
3.6	13.17	28.4	806.56	120.3	14472.09	14.7	216.09
24.5	600.25					110.9	12298.81
3.7	14.21					38.0	1444.00
11.0	121.00					58.4	3410.56
9.4	88.36						
10.3	106.09						
13.3	176.89						
10.7	114.49						
4.3	18.49						
9.3	86.49						
4.1	16.81						
21.7	470.89						
31.0	961.00						
35.8	1281.64						
66.9	4475.61						

APPENDIX C

TABLE 8. ACTUAL DATA OF PERMEABILITY VALUES (Cont'd)

THREE-INCH SPECIMENS		FOUR-INCH SPECIMENS			
CUBE		CORE		CUBE	
Y	Y^2	Y	Y^2	Y	Y^2
100.2	10040.04	135.7	18414.49	50.0	2500.00
65.4	4277.16	45.3	2052.09	132.9	17662.41
136.0	18496.00	48.6	2361.96	124.9	15600.01
139.9	19572.01	110.4	12188.16	134.2	18009.64
78.8	6209.44	66.6	4435.56	131.2	17213.44
108.6	11793.96	64.0	4096.00	136.2	18550.44
59.6	3552.16	96.0	9216.00	140.6	19768.36
122.0	14884.00	41.9	1755.61	41.0	1681.00
52.4	2745.76	37.2	1383.84	44.4	1971.36
119.4	14256.36	40.2	1616.04	99.3	9860.49
137.0	18769.00	46.4	2152.96		
103.7	10753.69	113.0	12769.00		
115.6	13363.36	131.5	17292.25		
134.5	18090.25	122.7	15055.29		
50.8	2580.64				
62.5	3906.25				

APPENDIX C
(Cont'd)

Actual Data of One-Inch Specimens

$Y = T_1 = 702.50$	$\bar{Y}_1 = 16.73$
$Y_{core} = 392.80$	$\bar{Y}_{core} = 14.03$
$Y_{cube} = 309.70$	$\bar{Y}_{cube} = 22.12$
$Y^2 = 23894.12$	$n_1 = 42$
$Y^2_{core} = 10657.53$	$n_{core} = 28$
$Y^2_{cube} = 13236.59$	$n_{cube} = 14$

Actual Data of Two-Inch Specimens

$Y = T_2 = 1338.10$	$\bar{Y}_2 = 43.16$
$Y_{core} = 613.10$	$\bar{Y}_{core} = 43.79$
$Y_{cube} = 725.00$	$\bar{Y}_{cube} = 42.65$
$Y^2 = 91974.75$	$n_2 = 31$
$Y^2_{core} = 44657.81$	$n_{core} = 14$
$Y^2_{cube} = 47316.94$	$n_{cube} = 17$

Actual Data of Three-Inch Specimens

$Y = T_3 = 1586.40$	$\bar{Y}_3 = 99.15$
$Y^2 = 173290.08$	$n_3 = 16$

APPENDIX C
(Cont'd)

Actual Data of Four-Inch Specimens

$Y = T_4 = 2134.20$

$Y_{core} = 1099.50$

$Y_{cube} = 1034.70$

$Y^2 = 227606.40$

$Y^2_{core} = 104789.25$

$Y^2_{cube} = 122817.15$

$\bar{Y}_4 = 88.92$

$\bar{Y}_{core} = 78.53$

$\bar{Y}_{cube} = 103.47$

$n_4 = 24$

$n_{core} = 14$

$n_{cube} = 10$

$$T = T_1 + T_2 + T_3 + T_4 = 5761.20$$

$$N = n_1 + n_2 + n_3 + n_4 = 113$$

$$\bar{Y} = \frac{T}{N} = 50.98$$

APPENDIX C
(Cont'd)

CALCULATIONS OF STANDARD DEVIATION (s)
AND COEFFICIENT OF VARIATION (c.v.)

One-Inch Specimens

Standard Deviation $s = \sqrt{s^2}$

$$s^2 = \frac{Y_{11}^2 + Y_{12}^2 + \ldots. + Y_{142}^2 - \frac{(T_1)^2}{42}}{42 - 1}$$

$$= \frac{23894.12 - 11750.15}{41} = 296.19$$

$s = 17.21$ millidarcies

$$\text{c.v.} = \frac{s}{\bar{Y}_1} \text{ X } 100\% = \frac{1721}{16.73}\ \% = 102.87\%$$

Two-Inch Specimens

$$s^2 = \frac{Y_{21}^2 + Y_{22}^2 + \ldots. + Y_{231}^2 - \frac{(T_2)^2}{31}}{31 - 1}$$

$$= \frac{91974.75 - 57758.43}{30} = 1140.54$$

$s = 33.76$ millidarcies

$$\text{c.v.} = \frac{s}{\bar{Y}_2} \text{ X } 100\% = \frac{3376}{43.16}\ \% = 78.22\%$$

Using the same method of calculations the following values were obtained:

Three-Inch Specimens

$s = 32.64$ millidarcies; c.v. = 32.92%

Four-Inch Specimens

$s = 40.55$ millidarcies; c.v. = 45.60%

APPENDIX C
(Cont'd)

TABLE 9. VALUES OF ORTHOGONAL COEFFICIENTS FOR COMPARISON OF TREATMENTS

COMPARISONS	TREATMENTS (SIZES)			
	1	2	3	4
C_4 : size 1 Vs. size 2	1	-1	0	0
C_5 : size (1 & 2) Vs. (3 & 4)	1	1	-1	-1
C_6 : size 3 Vs. size 4	0	0	1	-1
C_7 : size 2 Vs. size 3	0	1	-1	0
C_8 : size 1 Vs. size 4	1	0	0	-1
C_9 : size (1 & 4) Vs. (2 & 3)	1	-1	-1	1
C_{10}: size 1 Vs. size 3	1	0	-1	0
C_{11}: size 2 Vs. size 4	0	1	0	-1
C_{12}: size (1 & 3) Vs. (2 & 4)	1	-1	1	-1

APPENDIX D

SOME DERIVATIONS OF FORMULA USED IN THE STATISTICAL ANALYSIS

(i) Sum of Cross Products $= \sum_{i=1}^{N} X_i Y_i$

where: X_i is the size of specimen in inches,

$i = 1, 2, 3, 4$

Y_i is the true permeability value in millidarcies.

$$\begin{aligned}
\sum_{i=1}^{N} X_i Y_i &= 1(Y_{1-1}) + 1(Y_{1-2}) + \ldots. + 1(Y_{1-n_1}) \\
&+ 2(Y_{2-1}) + 2(Y_{2-2}) + \ldots. + 2(Y_{2-n_2}) \\
&+ 3(Y_{3-1}) + 3(Y_{3-2}) + \ldots. + 3(Y_{3-n_3}) \\
&+ 4(Y_{4-1}) + 4(Y_{4-2}) + \ldots. + 4(Y_{4-n_4}) \\
&= 1(Y_{1-1} + Y_{1-2} + Y_{1-3} + \ldots + Y_{1-n_1}) \\
&+ 2(Y_{2-1} + Y_{2-2} + Y_{2-3} + \ldots + Y_{2-n_2}) \\
&+ 3(Y_{3-1} + Y_{3-2} + Y_{3-3} + \ldots + Y_{3-n3}) \\
&+ 4(Y_{4-1} + Y_{4-2} + Y_{4-3} + \ldots + Y_{4-n_4}) \\
&= 1\,T_1 + 2\,T_2 + 3\,T_3 + 4\,T_4
\end{aligned}$$

(ii) Products of Totals $= (\sum_{i=1}^{N} X_i)\ (\sum_{i=1}^{N} Y_i)$

$$\begin{aligned}
\sum_{i}^{N} X_i &= \Big[(1 + 1 + \ldots + 1) + (2 + 2 + \ldots + 2) + (3 + \\
&\quad .. + 3 + \ldots + 3) + (4 + 4 + \ldots + 4)\Big] \\
&= 1\,n_1 + 2\,n_2 + 3\,n_3 + 4\,n_4
\end{aligned}$$

$$
\begin{aligned}
\sum_{i}^{N} Y_i &= (Y_{1-1} + Y_{1-2} + \dots + Y_{1-n_1}) \\
&+ (Y_{2-1} + Y_{2-2} + \dots + Y_{2-n_2}) \\
&+ (Y_{3-1} + Y_{3-2} + \dots + Y_{3-n_3}) \\
&+ (Y_{4-1} + Y_{4-2} + \dots + Y_{4-n_4}) \\
&= T_1 + T_2 + T_3 + T_4 \\
&= T = \text{total values of true permeability.}
\end{aligned}
$$

Thus, $(\sum_{i}^{N} X_i)\ (\sum_{i}^{N} Y_i) = (1\ n_1 + 2\ n_2 + 3\ n_3 + 4\ n_4)\ T$

(iii) Sums of Squares of $X = \sum_{i}^{N} X_i^2$

$$
\begin{aligned}
\sum_{i}^{N} X_i^2 &= (1^2 + 1^2 + \dots + 1^2) + (2^2 + 2^2 + \dots + 2^2) \\
&+ (3^2 + 3^2 + \dots + 3^2) + (4^2 + 4^2 + \dots + 4^2) \\
&= (1\ n_1 + 4\ n_2 + 9\ n_3 + 16\ n_4)
\end{aligned}
$$

(iv) $S\,S_{XY} = \sum_{i}^{N} X_i Y_i - \dfrac{(\sum_{i}^{N} X_i)\ (\sum_{i}^{N} Y_i)}{N}$

(v) $S\,S_{X} = \sum_{i}^{N} X_i^2 - \dfrac{(\sum_{i}^{N} X_i)^2}{N}$

APPENDIX E

```
      SELECTION NO. 1  SAMPLE SIZE  73  COMPARISON OF SIZES  1 - 2
 COEFFICIENT OF DETERMINATION  0.2101
 MULTIPLE CORR. COEFFICIENT    0.4584

 SUM OF SQUARES ATTRIBUTABLE TO REGRESSION       12243.29749
 SUM OF SQUARES OF DEVIATION FROM REGRESSION     46022.13037

 VARIANCE OF ESTIMATE      648.19901
 STD. ERROR OF ESTIMATE     25.45975

 INTERCEPT (A VALUE)    -9.23595



                ANALYSIS OF VARIANCE FOR THE MULTIPLE
                        LINEAR  REGRESSION

       SOURCE OF VARIATION          D.F.      SUM OF          MEAN          F
                                              SQUARES        SQUARES      VALUE
 DUE TO REGRESSION............       1     12243.29749   12243.29749    18.8882
 DEVIATION ABOUT REGRESSION...      71     46022.13037     648.19901
                     TOTAL...       72     58265.42822



 VARIABLE      MEAN         STD.         REG.      STD.ERROR     COMPUTED      PARTIAL
   NO.                   DEVIATION      COEFF.    OF REG.COE.    T VALUE     CORR. COE.
    1        1.42466      0.49771     26.20023     6.02851      4.34605       0.45840
    2       28.09041     28.44718
```

APPENDIX E (Cont'd)

```
        SELECTION NO. 2  SAMPLE SIZE  47  COMPARISON OF SIZES  2 - 3
COEFFICIENT OF DETERMINATION  0.3970
MULTIPLE CORR. COEFFICIENT    0.6301

SUM OF SQUARES ATTRIBUTABLE TO REGRESSION       33011.23193
SUM OF SQUARES OF DEVIATION FROM REGRESSION     50142.24072

VARIANCE OF ESTIMATE    1114.27200
STD. ERROR OF ESTIMATE    33.38071

INTERCEPT (A VALUE)   -68.69398



              ANALYSIS OF VARIANCE FOR THE MULTIPLE
                      LINEAR  REGRESSION

      SOURCE OF VARIATION        D.F.      SUM OF          MEAN          F
                                          SQUARES        SQUARES       VALUE
DUE TO REGRESSION............     1    33011.23193   33011.23193    29.6258
DEVIATION ABOUT REGRESSION...    45    50142.24072    1114.27200
                    TOTAL...     46    83153.47266



VARIABLE      MEAN         STD.         REG.       STD.ERROR     COMPUTED      PARTIAL
  NO.                    DEVIATION     COEFF.    OF REG.COE.    T VALUE     CORR. COE.
   1        2.34043       0.47898    55.92924     10.27552      5.44296       0.63007
   2       62.20425      42.51687
```

APPENDIX E (Cont'd)

```
        SELECTION NO. 3  SAMPLE SIZE  40  COMPARISON OF SIZES  3 - 4
 COEFFICIENT OF DETERMINATION  0.0181
 MULTIPLE CORR. COEFFICIENT    0.1347

 SUM OF SQUARES ATTRIBUTABLE TO REGRESSION          992.67015
 SUM OF SQUARES OF DEVIATION FROM REGRESSION      53748.61475

 VARIANCE OF ESTIMATE     1414.43723
 STD. ERROR OF ESTIMATE     37.60900

 INTERCEPT (A VALUE)    129.59992



                 ANALYSIS OF VARIANCE FOR THE MULTIPLE
                          LINEAR  REGRESSION

      SOURCE OF VARIATION          D.F.     SUM OF          MEAN          F
                                            SQUARES        SQUARES      VALUE
 DUE TO REGRESSION............      1     992.67015      992.67015     0.7018
 DEVIATION ABOUT REGRESSION...     38   53748.61475     1414.43723
                     TOTAL...      39   54741.28516



 VARIABLE      MEAN       STD.        REG.      STD.ERROR      COMPUTED      PARTIAL
   NO.                 DEVIATION     COEFF.    OF REG.COE.    T VALUE     CORR. COE.
    1        3.60000    0.49614   -10.16873    12.13825      -0.83774      -0.13466
    2       92.99249   37.46495
```

APPENDIX E (Cont'd)

SELECTION NO. 4 SAMPLE SIZE 113 COMPARISON OF SIZES 1 - 2 - 3 - 4

```
COEFFICIENT OF DETERMINATION  0.4860
MULTIPLE CORR. COEFFICIENT    0.6972

SUM OF SQUARES ATTRIBUTABLE TO REGRESSION      107831.29102
SUM OF SQUARES OF DEVIATION FROM REGRESSION    114023.77539

VARIANCE OF ESTIMATE     1027.24121
STD. ERROR OF ESTIMATE     32.05060

INTERCEPT (A VALUE)     -7.83473



              ANALYSIS OF VARIANCE FOR THE MULTIPLE
                      LINEAR  REGRESSION

      SOURCE OF VARIATION          D.F.      SUM OF          MEAN           F
                                             SQUARES        SQUARES       VALUE
DUE TO REGRESSION............        1    107831.29102  107831.29102   104.9717
DEVIATION ABOUT REGRESSION...      111    114023.77539    1027.24121
                      TOTAL...     112    221855.06641



VARIABLE      MEAN         STD.         REG.      STD.ERROR      COMPUTED      PARTIAL
  NO.                    DEVIATION     COEFF.    OF REG.COE.    T VALUE     CORR. COE.
   1        2.19469      1.15618     26.83719     2.61939      10.24557       0.69717
   2       51.06459     44.50673
```

APPENDIX E (Cont'd)

```
      SELECTION NO. 5  SAMPLE SIZE  55  COMPARISON OF SIZES  2 - 4
COEFFICIENT OF DETERMINATION  0.2822
MULTIPLE CORR. COEFFICIENT    0.5313

SUM OF SQUARES ATTRIBUTABLE TO REGRESSION      28326.40771
SUM OF SQUARES OF DEVIATION FROM REGRESSION    72038.99023

VARIANCE OF ESTIMATE    1359.22623
STD. ERROR OF ESTIMATE    36.86769

INTERCEPT (A VALUE)    -2.59597



              ANALYSIS OF VARIANCE FOR THE MULTIPLE
                        LINEAR  REGRESSION

     SOURCE OF VARIATION        D.F.     SUM OF        MEAN          F
                                         SQUARES       SQUARES      VALUE
DUE TO REGRESSION............    1     28326.40771  28326.40771   20.8401
DEVIATION ABOUT REGRESSION...   53     72038.99023   1359.22623
                     TOTAL...   54    100365.39844


VARIABLE     MEAN        STD.        REG.      STD.ERROR     COMPUTED     PARTIAL
  NO.                  DEVIATION    COEFF.    OF REG.COE.   T VALUE     CORR. COE.
   1       2.87273     1.00101    22.88024    5.01200      4.56510      0.53126
   2      63.13272    43.11170
```

APPENDIX E (Cont'd)

SELECTION NO. 6 SAMPLE SIZE 58 COMPARISON OF SIZES 1 - 3

```
COEFFICIENT OF DETERMINATION  0.7381
MULTIPLE CORR. COEFFICIENT    0.8591

SUM OF SQUARES ATTRIBUTABLE TO REGRESSION       78151.84570
SUM OF SQUARES OF DEVIATION FROM REGRESSION     27731.75098

VARIANCE OF ESTIMATE      495.20984
STD. ERROR OF ESTIMATE     22.25331

INTERCEPT (A VALUE)    -24.10045



              ANALYSIS OF VARIANCE FOR THE MULTIPLE
                     LINEAR  REGRESSION

     SOURCE OF VARIATION        D.F.      SUM OF          MEAN         F
                                          SQUARES        SQUARES      VALUE
DUE TO REGRESSION............    1      78151.84570    78151.84570  157.8156
DEVIATION ABOUT REGRESSION...   56      27731.75098      495.20984
                     TOTAL...   57     105883.59668


VARIABLE      MEAN        STD.        REG.     STD.ERROR     COMPUTED      PARTIAL
  NO.                   DEVIATION    COEFF.   OF REG.COE.    T VALUE    CORR. COE.
   1        1.55172     0.90170    41.06473    3.26884     12.56247      0.85912
   2       39.62069    43.09996
```

APPENDIX E (Cont'd)

```
      SELECTION NO. 7  SAMPLE SIZE   66  COMPARISON OF SIZES  1 - 4
COEFFICIENT OF DETERMINATION  0.6144
MULTIPLE CORR. COEFFICIENT    0.7839

SUM OF SQUARES ATTRIBUTABLE TO REGRESSION        79087.44141
SUM OF SQUARES OF DEVIATION FROM REGRESSION      49628.48633

VARIANCE OF ESTIMATE       775.44510
STD. ERROR OF ESTIMATE      27.84681

INTERCEPT (A VALUE)     -7.02262



             ANALYSIS OF VARIANCE FOR THE MULTIPLE
                        LINEAR  REGRESSION

      SOURCE OF VARIATION          D.F.       SUM OF          MEAN          F
                                              SQUARES         SQUARES       VALUE
DUE TO REGRESSION............       1      79087.44141    79087.44141    101.9897
DEVIATION ABOUT REGRESSION...      64      49628.48633      775.44510
                    TOTAL...       65     128715.92773



VARIABLE       MEAN          STD.          REG.       STD.ERROR      COMPUTED       PARTIAL
  NO.                      DEVIATION      COEFF.     OF REG.COE.   T VALUE       CORR. COE.
   1         2.09091       1.45420      23.98690      2.37518      10.09900        0.78386
   2        43.13181      44.49994
```

EFFECTS OF SIZE AND SHAPE OF SPECIMENS AND GAS SLIPPAGE PHENOMENA IN THE MEASUREMENT OF COAL PERMEABILITY TO GAS FLOW

by Ambyo Sumopandhi Mangunwidjojo

ABSTRACT

The flow of fluids through porous materials is a subject of importance in the study of the gas emission in coal mines. Air is commonly used as the fluid medium in gas permeability tests. In this case, it is advisable to take into account the existence of gas slippage phenomena. The experimental results showed that the value of the observed permeability is always larger than the true permeability by 25 to 150 per cent.

The geometrical shape of the specimen has no effect on the permeability value. Comparisons were made for cylindrical specimens of one inch, two inch, and four inch diameters versus the corresponding dimensions of the cube specimens.

It has been found that the permeability value of coal increases with an increase in specimen size. The experimental results showed that specimen size of three inches in diameter can be considered as the representative size for coal permeability for the coal tested.