A STUDY OF THE FACTORS THAT AFFECT THE PERMEABILITY OF COAL

by

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PURPOSE OF STUDY

At the present time considerable attention is being given to the degasification of coal beds. The purpose of this degasification is first to reduce the amount of inflammable gas that must be handled in coal mine ventilation systems and second to make some economical use of the vast amount of inflammable gas that is released during coal mining.

The natural coal gas evolved during the formation of coal was partially retained in the coal itself and was entrapped in the adjacent strata if they were permeable to the gas. The natural coal gas consisted of a high percentage of methane. When this gas is emitted from the strata and coal bed into the mine's atmosphere an explosive mixture with the mine's atmosphere may form which if ignited will cause a mine explosion. This problem is still one of the most difficult and serious hazard to be overcome in coal mining.

The amount of natural coal gas released from the coal mines in West Virginia is equal to, or even greater than, the state's production of natural gas[1*]. Lawall and Morris' paper[2] reported data from six mines in Southern West Virginia and indicated that about 23 million cu.ft. of the gas is liberated per 24 hrs. during normal coal production. Therefore if an economical way of recovering the natural coal gas

*References are listed in the bibliography of this study.

could be found the output of natural gas in West Virginia, for example, could be greatly increased.

The broad problem of degasification of coal beds can hardly be solved without sufficient information pertaining to factors such as geological formations of the coal bed, characteristics of the coal, porosity, and permeability of the coal, and the physical as well as chemical correlation between the gas and the coal, etc.. From the practical point of view, the permeability of coal may be considered as a measure of the ease with which gas flows through the coal bed. Since the permeability of coal is of particular importance in the problem of degasification, the relative factors affecting the permeability of coal can not be neglected. This study, therefore, is concerned with the factors which affect the permeability of coal.

SUMMARY OF LITERATURE PERTAINING TO THE PERMEABILITY OF COAL AND THE FACTORS AFFECTING IT

(A) General concept of the permeability of coal

The theory of single phase, linear flow through homogeneous porous media comes from the experimental works of Henry Darcy. The generalized Darcy's Law[3] for homogeneous fluid flowing through porous media may be stated as

$$V_s = - \frac{K}{u} \left(\frac{dp}{ds} - qg \cos \theta \right) \quad (1)$$

Where V_s is the fluid velocity in the direction S, making an angle θ with the vertical, u, q, and p are the viscosity, density, and pressure of the fluid respectively, and g is the acceleration due to gravity, the constant K is called the permeability of the medium. This equation is a differential relationship pertaining to any point within the porous medium, so that V_s is to be considered as a function of that point, as must also p, $\frac{dp}{ds}$, θ, and even q if the fluid is compressible, and u is also to be considered as a variable and is ultimately dependent on S, if the conditions dictate that such a variation should be taken into account, The permeability coeffecient K is the unique factor, representing the porous medium.

If the exposed surface of the porous medium be set perpendicular to the direction of gas flow, then, there will be no angle θ existing and if the gravitational force and density are considered to be so small that they can be neglected, then, the equation can be rewritten as

$$V_x = - \frac{K}{u} \frac{dp}{dx} \tag{2}$$

Where V_x is the velocity in the direction x and $\frac{dp}{dx}$ is the pressure gradient in the same direction.

In the case of gaseous fluid measurement, it is usually known that gas is compressible. Therefore, as the gas falls in pressure while flowing through the porous medium, the volume flow v will no longer be constant. However, the mass flow qv will be constant. For isothermal conditions, the gas density q will be proportional to the pressure thus making pv or p $\frac{dp}{dx}$ constant. Then

$$2p\frac{dp}{dx} = \frac{dp^2}{dx} = \text{const.} = (p_1^2 - p_2^2)/L = 2p\ (p_1 - p_2)/L$$

where P is the mean pressure or $(p_1 + p_2)/2$.

Upon applying equation (2), it follows that

$$K = \frac{uVx}{dp/dx} = \frac{2upVL}{(p_1^2 - p_2^2)} = u\ p\ V\ L/P\ (p_1 - P_2)$$

where V refers to the volume flow per unit area at the pressure p, then $pV/P = \bar{\bar{v}}$, it is the volume flow at mean pressure P. Therefore

$$K = u\ \bar{\bar{v}}\ L/(p_1 - p_2) = u\ \bar{\bar{v}}\ A\ L/A\ (p_1 - p_2)$$

$$= u\, Q\, L / A\, (p_1 - p_2) \tag{3}$$

Here Q is the flow rate in c.c. per sec. at the mean pressure P, A is the exposed surface of the porous medium in cm^2., u is the viscosity of the gas ous fluid in centipoises, L is the thickness of the porous medium in cm., p_1 and p_2 is the pressure upstream and downstream respectively in atmospheres, and the permeability K of the porous medium in darcys (1 darcy equal 1,000 millidarcys). Equation (3) is used to determine the permeability of coal by considering the coal as a porous medium and the air as the gaseous fluid.

The permeability of coal, now, can be defined as a measure of the ease with which the gaseous fluid flows through the coal. For a known gradient pressure or pressure drop from end to end, the flow rate of gaseous fluid is proportional to the permeability of coal.

(B) Factors that affect the permeability of coal .

Since the permeability of coal has been defined as a measure of the ease with which the gaseous fluid flows through the coal under a known pressure gradient, the factors that affect the permeability of coal are governed by both the properties of the coal, the gaseous fluid, and their correlation. Among these factors, the major ones are as follows:

(1) Geometrical property of porous media

Obviously, permeability can exist in a medium which consists of pores that are interconnected one to another, so called effective pores, to form tube shape channels. For without these effective pores, there would be no openings for the gas to flow through. It is reasonable to say that the flow rate of the gas through a porous medium will generally increase if the medium consists of more of the effective pores. And it is supposed that there would be certain relations between the quantity of the pores and the permeability. Unfortunately, there is little information available to indicate the relationship between pore quantity and permeability of coal. Some experiments have been made to find this geometrical quantity to characterize the porous medium of reservoir rocks. Most of the experiments are based on (a) porosity and (b) capillary pressure curve, which are briefly reviewed here to give an idea of what the relation is between the permeability to the porosity, and the capillary pressure curve established.

(a) Porosity

Porosity is defined as the ratio of the total void space in a medium to the total volume of the medium and it is usually expressed in percent. The result of experiments on the relationship between the permeability and the porosity of reservoir rocks have shown [4] that when the permeability is plotted on a logarithmic scale and the porosity on a linear scale, there is a proportional relationship for each rock sample. However, in a single formation there can be different values of permeability for the same values of porosity, therefore other factors must be considered to determine the permeability.

(b) Capillary pressure curve

Another attempt to measure the geometrical quantity of the pores in a porous medium is termed "capillary pressure curve." It is usually obtained by measuring the quantity of the fluid being absorbed by the porous medium under a known pressure. The capillary pressure curve[3, 6] shows that the capillary pressure is inversely proportional to the degree of saturation. From Wallace's work[5], it is shown that the permeability of various sand samples is proportion to the degree of saturation. It seems that the permeability of a porous medium increases with a decrease in the capillary pressure within the porous medium. Yet, two sand samples of the same degree of saturation can have entirely different permeabilities.

(2) Properties of the fluid

Fluid flow through porous medium is completely a dynamic problem. There are three physical conditions which govern the problem namely (a) continuity, (b) Newton's law of motion, and (c) rheological condition. It may be considered that the pores of a body of coal are continuously filled with gas which discharges at a free face. The increase or decrease in the mass of the exit gas is equal to the loss or gain of the mass of the porous medium respectively, this is the theory of continuity. The force which drives the gas through the coal bed is caused by underground pressure. The rheological conditions usually assumes that the gas is viscous and compressible. Because of the compressibility of a gaseous fluid, the following general equation[7] can be assumed as

$$P V = Z n R T \tag{4}$$

where P is the absolute pressure in atmosphere, V is the volume in liters, n is the fraction of molecular weight in grams per molecular weight, R is the gas constant in liter atm. per degree C per mole, and T is the absolute temperature Kelvin (equals centigrade temperature plus 273), and Z is the gas compressibility factor. For an ideal gas Z is equal 1, and for a non-ideal gas, Z is greater or less than 1 depending on the pressure and temperature. This compressibility factor can be found in Burcik's work[7] (Fig.6-10) after the reduced pressure and temperature are found. The reduced pressure is the ratio of the pressure to the critical pressure, and the reduced temperature is the ratio of the temperature to the critical temperature. Further the viscosity of the gas varies also depending on temperature and pressure, thus any change of the temperature and pressure will greatly affect the behavior of the gas.

Equation (3) for determining the permeability of coal is based upon Darcy's Law, and on the assumptions of (a) a homogeneous and steady flow, (b) an isothermal process, (c) neglect of the density of air and of gravitational force, and (d) use of a single dimension.

(3) Adsorption and discharge of gas by coal

The significant relation of coal to the gas is expansion and contraction of the coal with adsorption and discharge of the gases. Under pressure, coal can absorb large quantities of gases, and by releasing the pressure, the gas is again set free. Experiments concerning these factors have been carried out by Briggs and Sinha[8]. Briggs stated that a coal face is full of small cracks, and it is natural to attribute them to pressure or relief of pressure; but it appears probably that these cracks are due partly to shrinkage resulting from gas emission. These cracks must extend a great distance into the coal bed. Being open channels, they facilitate the drainage of the gas, and by relieving the gas pressure they become the means of their own extension. Once an opening is made in a seam, there would appear to be no limit to their development unless the seam is cut off by a fault or other disturbance. In Maas' paper[9], the adsorption-isotherm curve shows that the adsorbed methane in coal is proportional to the pressure.

If an adsorbable gas, as hydrocarbon gas is absorbed by coal, is confined within the pores of coal, then the relation between the pressure and the volume of the gas is not the same as if the gas was confined in a vessel of the same volume as the pore spaces in the coal. Thus the adsorption affects the gas behavior in the coal.

(4) Overburden pressure

At great depth in sedimentary rocks, interbedded coal beds are being deformed due to the overburden load and lateral pressure. This deformation will reduce the size of the pores in the coal bed. Therefore the permeability of the coal will certainly be affected. The change in permeability with overburden pressure has been shown in Fatt and Davis'[10] experimental works with reservoir rocks from different regions. The results showed that the percent of reduction of the permeability (Permeability with pressure/ Permeability without pressure X 100 = Percent of reduction) as a function of overburden pressure is inversely proportion within a certain range of pressure. However, it shows only a qualitative significance, because of the difficulty in reproducing the true overburden pressure found in the earth.

(5) Directional influence

Obviously, the permeability of coal would be affected by the direction of flow and the face on which the flow is acting, even though the flow is confined to one dimension. This is due to irregular formation of pores through which the gas flows. Pressler[11] stated that the porosity of the oil producing reservoir rock found in Florida ranges from 15 to 24.5 percent with an average permeability of 312 md. (millidarcys) when measured parallel with the bedding and 84 md., when measured perpendicular to the bedding. In Scheidegger's work[6] on gas sands, the directional permeability was measured in intervals from 0 to 180 degrees on a number of small sections, each section was cut from the sample rock so that its face was perpendicular to the desired angle of flow to be measured. The results were plotted on polar permeability diagrams and formed an ellipsoidal shape. Therefore, a directional variation of the permeability can be anticipated.

CONCERNING THE FACTORS THAT MAY AFFECT THE PERMEABILITY OF COAL IN A COAL BED

Because of the differences in type and rank of individual coal beds, and the regional environment of certain mines, the permeability of coal varies from one bed to another which is to be expected. The geological formations and mining methods are the main factors affecting the permeability. These factors can be stated roughly as follow:

(1) Porous overburden and formation of fissures

Coal was usually buried in a layer form under a series of sedimentary rocks such as shales, clays, conglomerates, limestones and sandstones. The type of rocks and geological deformation of rock layers forming the cover of coal beds may have greatly influenced the permeability of coal. This significant influence may be explained by a change in the rank of coal, as a carbon enrichment process.

The carbon enrichment process in a coal bed is a combination of the alteration of the coal bed and its devolatilization. Porous overburden and the formation of fissures due to the geological disturbance have undoubtly provided passage ways for gases and volatile matter to escape. Thus the coal lying at lower levels always contains less volatile matter and more carbon than the coal lying at a higher level, (Hilt's Law[16]), because of heavy overburden, lateral pressure, and an adequately long duration of time for the volatile matter to escape.

Apparently, gas escapes from coal beds more readily through fissures and cracks than through pores. The gas pressure in the coal bed itself varies with such gas escape through fissure and pores in the overburden.

(2) Difference in location in the same bed

Apparently, the difference in location in the same coal bed may be considered as a factor that will affect the permeability of coal, because the gas pressure in the coal bed and the overburden pressure on the bed varies from location to location. The coal permeability decreases with increased overburden pressure as stated before. Referring to the gas pressure, the location is a paramount factor in the gas pressure that exists in the solid coal at any one place[2]. The gas pressure in the coal bed has been investigated by Lawall and Morris[2]. The maximum pressure could hardly be obtained because the gas pressure intensity could not be measured to a very high degree of accuracy. It may be said, in general, that the gas pressure increases as the solid coal is penetrated and probably reaches a maximum some distance from the face. It is known that the gas is irregularly distributed in the coal itself and because of numerous other conditions such as joint planes, slips and fractures, and change in the physical character of the coal bed from place to place. No doubt, the variation of gas pressure would affect the coal permeability.

(3) Different benches

Individual benches of a single coal bed commonly have somewhat different composition, lamination and structural disturbance. Because of these differences, a variation in permeability might be expected. The benches have impurities in the forms of rocks, minerals, and air pockets. These impurities are introduced into the benches during their formation. Also fissures which form after the bench was built up may be filled with grains of sedimentary rocks. The combination of these two factors can change the system of pores throughout the bench and from one bench to another. The lamination of coal may be considered as orienting the gas flow through the coal. If the coal bed lay between two very clayey slates, which are highly plastic, then fracture in the clays can not take place and the gas flows along the laminations. Further, each bench of a coal bed may be under a different stress because of the structural disturbances of the coal bed. Thus all these conditions affect the permeability of coal.

(4) Water and gas contents in the coal bed

Coal beds are accompanied by sedimentary rock layers which are also permeable to water and will conduct it. This is another important factor. Not only do the fissures of these layers conduct water, but, sometimes, the coal bed itself is permeable to water. Water is absorbed more readily than gas by dry coal as pointed out in Brigg's and Sinha's[8] paper. If the pore spaces in the coal are occupied by absorbed water, the water in the channels will produce higher resistance to the flow of gas. It might be thought that the permeability of coal will decrease with an increase in the amount of water absorbed in the coal.

The natural coal gas is formed by the decomposition of organic material. This gas is usually tightly included in the coal bed itself and released by the removal of pressure by mining. It may flow evenly through pores and fissures of the coal or brust out suddenly, depending on the quantity and the pressure of accumulated gas. Then, in case of even liberation of the gas through the pores and fissures, the rate of liberation will partly depend on the quantity of gas evolved in the coal bed.

(5) Influence of mining method and cleavages due to mining

When openings are made due to mining, the overburden pressure right over these openings will be distributed over the opening boundaries. As this opening releases the pressure, the gas flow from the coal bed will be toward the opening. In general, the concentration and rapid advancement of mining the coal will increase the amount of methane liberated, as stated in Maas' paper[9]. In other words, the amount of liberated methane is proportional to the amount of coal being mined. Chambelin[12] found that the emanation rate of the gas is increased by crushing the coal. It seems that the mechanization of a mine, by using a "continuous miner" which operates in a coal mine with a high rate of advance, and high rate of tonnage production, and also crushes the coal into rather small pieces, causes ventilation trouble when trying to dilute the additional amount of methane liberated. Thus, the liberation of methane and its concentration are related to the method of mining. Further, ruptures and fissures of the accompanying rock layers as well as coal bed itself might be the result of mining. Consequently, the permeability of the coal bed may also be influenced by cleavages due to mining.

LABORATORY INVESTIGATION OF SOME OF THE FACTORS THAT AFFECT THE COAL PERMEABILITY

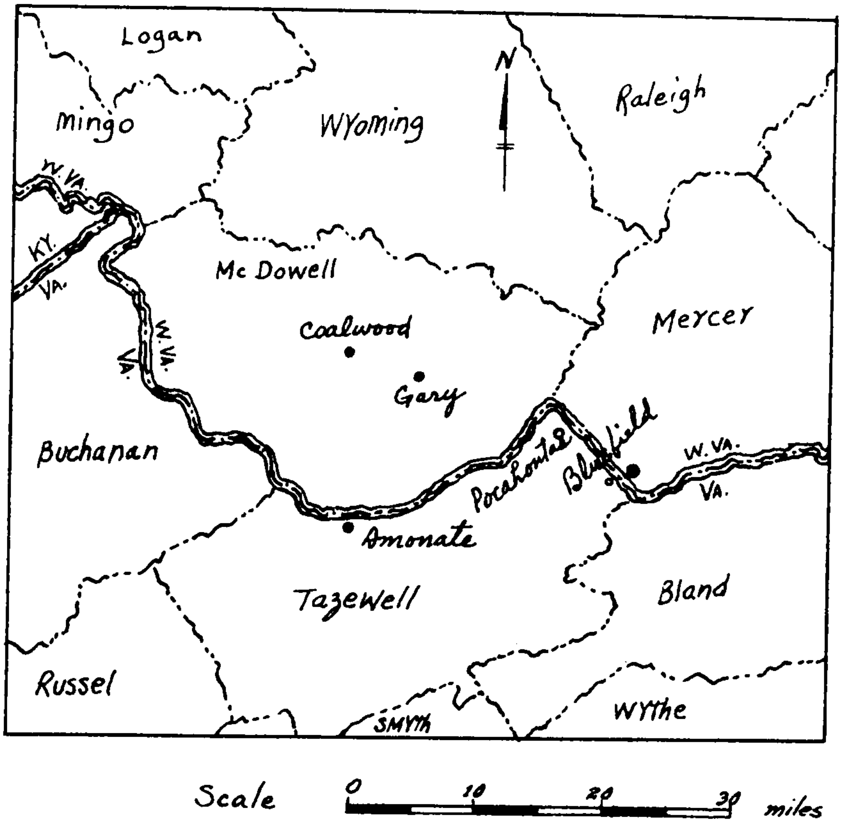
The laboratory investigation of this study has been carried out upon these factors namely (a) permeability tests parallel to coal bedding, (b) permeability tests on water soaked samples (parallel to coal bedding), (c) permeability tests perpendicular to coal bedding, and (d) permeability tests with respect to different benches of the coal bed (parallel to coal bedding), and (e) permeability tests of coal from different location in the same bed.

(A) Testing

(a) Preparing the coal samples

The coal samples were taken from operating mines in the Pocahontas No. 4 coal bed. These mines are (1) Olga Coal Company, Coalwood, West Virginia, (2) U.S. Steel Corp. Mine No. 2, Gary, West Virginia, and (3) Pocahontas Fuel Company, Pocahontas, Virginia, Amonate Mine, Virginia. The coal samples for testing of different benches were taken from Pocahontas Fuel Company, Amonate Mine. The locations of the above named mines are shown in Figure 1.

The coal samples randomly selected were cut into about 1 inch cubes from the coal lumps, the face of the cubes being parallel and perpendicular to coal laminations, by means of a water lubricated power driven diamond saw. Then



• Sample Location

Figure 1. **Location of Coal Samples Obtained for Permeability Tests**

they were polished down into cubes about 2 cm. on a side with sand paper. Then the cross-sectional area and thickness of the samples were measured. Coal is a very delicate substance, especially low volatile bituminous coal, and would be crushed when clamped in the sample holder of the permeameter. Therefore, it was required that the samples be imbedded into a metal sleeve by using sealing wax. The imbedding was such that in some samples the gas was allowed to flow through the sample parallel to the coal bedding and in others the gas was allowed to flow perpendicular to the bedding. The metal sleeve with coal sample was then clamped into the sample holder of the permeameter.

(b) Apparatus for testing the permeability of coal

Since there is no standard apparatus for testing coal permeability, a Ruska gas permeameter[13], which is employed by the petroleum industry for measuring the permeability of reservoir rock samples, was used. The measurement of the permeability of the coal was made by forcing an air of known viscosity through a coal sample of known cross sectional area and thickness. Pressure, temperature and flow rate of the gas through the sample were measured. A diagram of the apparatus used for testing the permeability of coal is shown in Figure 2, in which A is an air compressor with an out-let valve (1); B is the air drier with an out-let valve (2); C is the instrument for obtaining water saturated

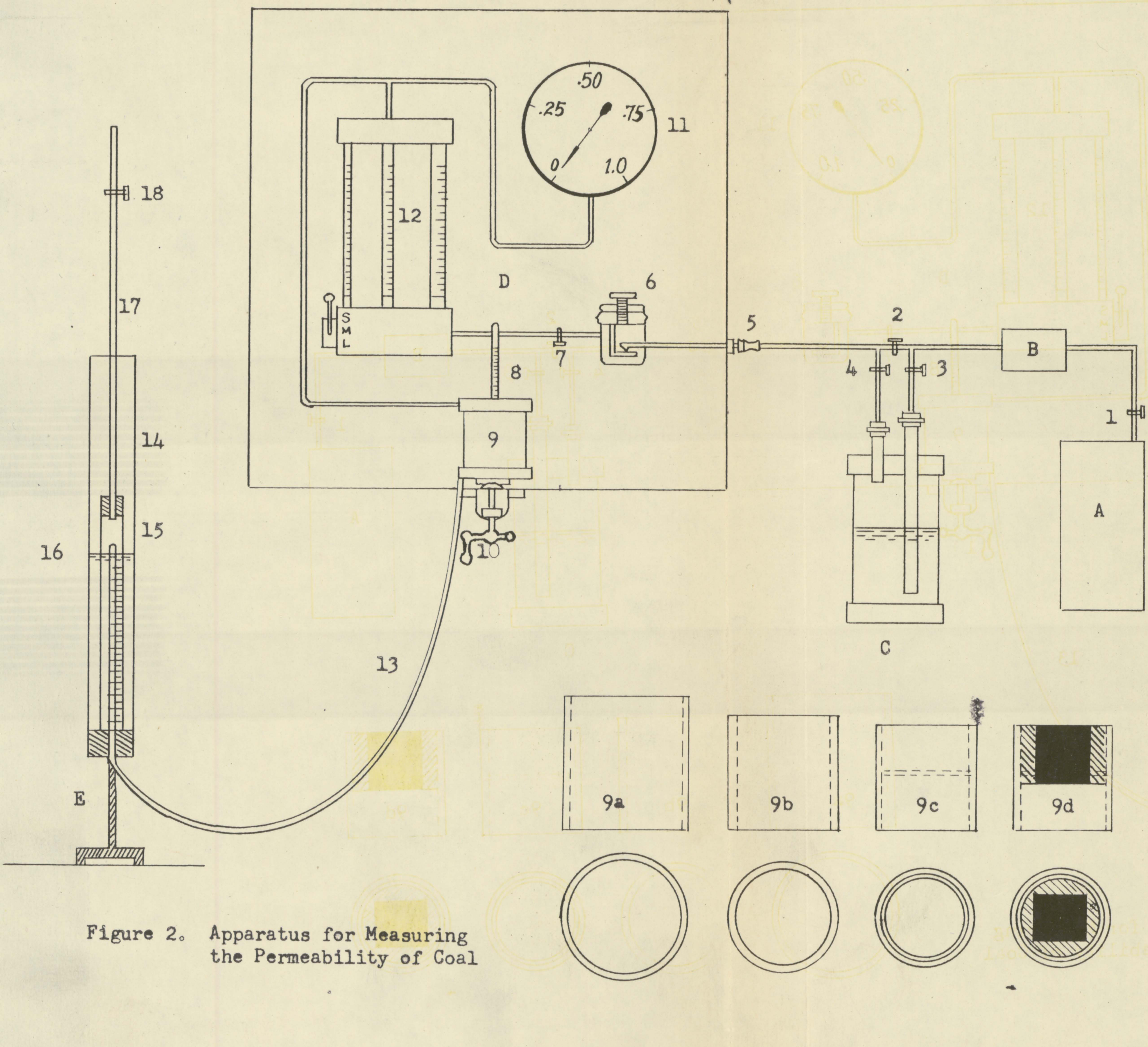


Figure 2. Apparatus for Measuring the Permeability of Coal

air which was used only on tests of the permeability of water soaked coal samples, and in dry tests to prevent the air from carrying moisture from the coal samples. If the moisture in the coal sample is carried out by air flow, the coal permeability of later measurements will be affected. To obtain the water saturated air, close valve (2) and open valves (3) and (4); D is the Ruska gas permeameter which consists of a sample holder (9) with a built-in thermometer (8), triple range flowmeter with a selector valve (12), hand calibrated board on tube pressure gage (11), pressure regulator (6) with air in-let connection (5). The pressure regulator is equipped with a bleed screw (7) which permits a small amount of the air to leak into the atmosphere. This leakage permits better up-stream pressure regulation and more sensitive pressure adjustment. (10) is a tightening screw which tightens the sample holder; E is an instrument to facilitate a comparison between different gradient pressures for collecting the air, which flows through the samples, or instead lets the air flow into the atmosphere as originally designed. It may be said that instrument E is used instead of the flowmeter (12) on gas permeameter D. The air flows through the coal sample, a rubber hose (13), and the pipettes (15) and (17) to the atmosphere, or it can be collected in pipette (15) if the valve (18) is closed. The air accumulated in pipette (15) will force the water level down and raise the water level up in pipette (14). Thus, from the scale of pipette (15), a certain amount of air can be read within a certain time, and from the difference in water levels in pipettes (15) and (14), the pressures can be calculated individually because pipette (14) is exposed to atmosphere pressure.

(c) Procedures

In this study, the permeability is measured by forcing air into the coal samples with the flow parallel to the axis of the bedding or perpndicular to the axis of the bedding. Thus, the coal samples are mounted in metal sleeves with respect to these axis.

Physically, the procedures of measuring the coal permeability is quite simple. The void space of the sleeve after the coal sample has been mounted has to be measured before testing and so does the void spaces in the rubber hose (13), in pipette (17) up to the valve (18). By pushing the metal sleeve of the mounted sample (9d) into a rubber sleeve (9b) of the corresponding size which is then inserted into the sample holder sleeve (9a) and locking tight by the tightening screw (10) which are combined into (9) as shown in Figure 2. (9c) is a metal sleeve before the coal sample has been mounted with sealing wax, the valves (1) and (2)are then opened. The pressure regulating valve is slowly opened until the pressure gage reads the desired gradient pressure (atm.). It is advisable to tap the pressure gage glass lightly while the pressure is being adjusted. After a few minutes, close valve (18), and the air which flows through the coal sample is accumulated in pipette (15), record the time using a stop watch required for a certain volume, measured in c.c., of air accumulation, under a known gradient pressure. The temperature is read from the thermometer and the difference in the water level in pipettes (14) and (15) is measured. These measurements can now be used for calculations.

When testing the water soaked coal samples, the samples used were exactly the same as these used for tests when flow is paralled to the bedding; however, the samples are placed in water for 24 hours before being tested. The procedure is the same as above, the only difference is that valve (2) is closed and valves (3) and (4) are opened. In order to use the same samples for perpendicular-to-the-bed testing, the samples are taken out of metal sleeves (9d) after gentle heating and then the sealing wax is scraped off with a heated knife. After the surfaces have been cleaned by lightly polishing with sand paper, dry the sample then mount them in the metal sleeve with sealing wax so that the gas must flow through them in a direction that is perpendicular to the laminations. Then allow time for the sealing wax to cool. The samples are now ready for the perpendicular-to-the-bedding testing. The procedures for making this test are the same as for making parallel-to-the-bedding tests.

(B) Calculating

The permeability of coal is computed by the equation

$$K = u\,Q\,L\,/\,A\,(p_1 - p_2)$$

as stated in part II.

Sample calculation

A coal sample has the dimensions 1.91 cm. X 1.87 cm. X 1.90 cm. of length, breadth, and thickness respectively, and has been mounted in a metal sleeve using sealing wax. The total void space of the coal sample mounted sleeve, of the rubber hose, of pipettes (16), (15), and (17) up to valve (18) is 45.5 c.c.. After testing, the time required for 10 c.c. of air to be accumulated in pipette (15) as shown in Figure 2. under corresponding pressure gradients is listed as follows:

Gradient pressure (atmosphere)	Time (in sec. to pass 10 c.c.)	Temperature (degree C.)
0.25	324	21
0.50	156	21
0.75	103	21
1.00	73	21

The difference between the water levels in pipettes (14) and (15) is 18 cm. after collecting 10 c.c. of air. The

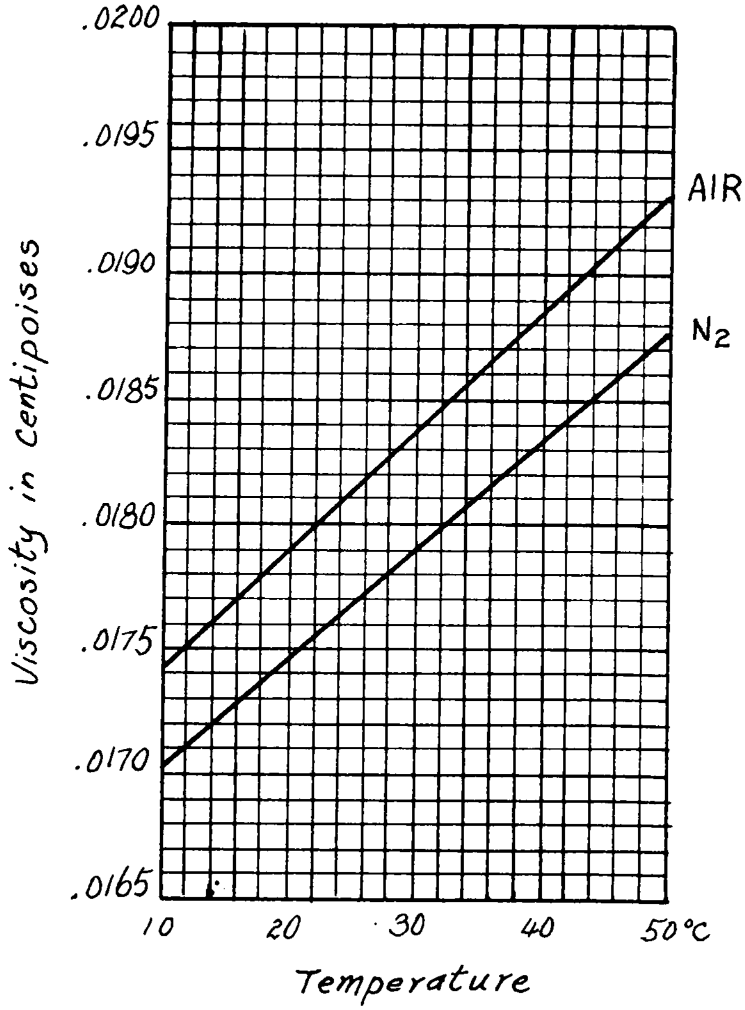


Figure 3. Gas Viscosity
(from reference No. 13)

pressure in pipette (15) is 18 cm. of water head greater than pipette (14) which is exposed to the atmosphere. The viscosity of air at 21 degree C. is 0.01795 centipoise, or it is found from Figure 3.

After 10 c.c. of air fills pipette (15), there is a total volume of 45.5 + 10 = 55.5 c.c. of air in the system which is under the pressure of 1 atmosphere plus 18 cm. water head. The 18 cm. of water head is now converted to atmosphere pressure. Since $pv = p'v'$ in a isothermal process, then $v = v'p' / p$. In this example, $v' = 55.5$ c.c., $p' = 1{,}033.6 + 18$ g./ $cm.^2$, and $p = 1{,}033.6$ g. / $cm.^2$. Then

$$v = 55.5 \times 1{,}051.6 / 1{,}033.6 = 56.47 \text{ c.c.}$$

Substracting the original void space, the air passing through the coal will be

$$56.47 - 45.5 = 10.97 \text{ c.c.}$$

which has to be converted into main pressure volume as follows:

$10.97 \times 1/ (1.0174 + 1.25)/2 = 9.67$ c.c.

$1/ (1.0174 + 1.50)/2 = 8.71$ c.c.

$1/ (1.0174 + 1.75)/2 = 7.93$ c.c.

$1/ (1.0174 + 2.00)/2 = 7.27$ c.c.

then Q will be

$9.67/324 = 0.030$ c.c./sec.

$8.71/156 = 0.056$ c.c./sec.

$7.93/103 = 0.077$ c.c./sec.

$7.27/73 = 0.100$ c.c./sec.

and gradient pressure ($p_1 - p_2$) will be

$1.25 - 1.0174 = 0.233$ atm.

$1.50 - 1.0174 = 0.483$ atm.

$1.75 - 1.0174 = 0.733$ atm.

$2.00 - 1.0174 = 0.983$ atm.

The viscosity $u = 0.01795$ centipoise (from Fig. 3)

The sample area $A = 1.91 \times 1.87 = 3.573$ cm^2.

The thickness $L = 1.90$ cm.

substituting in the equation $K = uQL/A\ (p_1 - p_1)$, then

$K = 0.01795 \times 1.90/3.57 \times 0.030/0.233 = 1.225 \times 10^{-3}$ darcys

$0.056/0.483 = 1.105 \times 10^{-3}$ darcys

$0.077/0.733 = 1.002 \times 10^{-3}$ darcys

$0.100/0.983 = 0.967 \times 10^{-3}$ darcys

with an average of 1.070×10^{-3} darcys or 1.070 millidarcys. If the permeabilities are plotted with respect to their different pressure gradients, the curve is shown as following Figure 4. The permeability is not quite a unique factor. It has a downward tendency with higher pressure gradient.

(C) Results

(a) The coal permeabilities

The coal permeabilities have been measured and calculated. The results are listed as follows in Table 1.

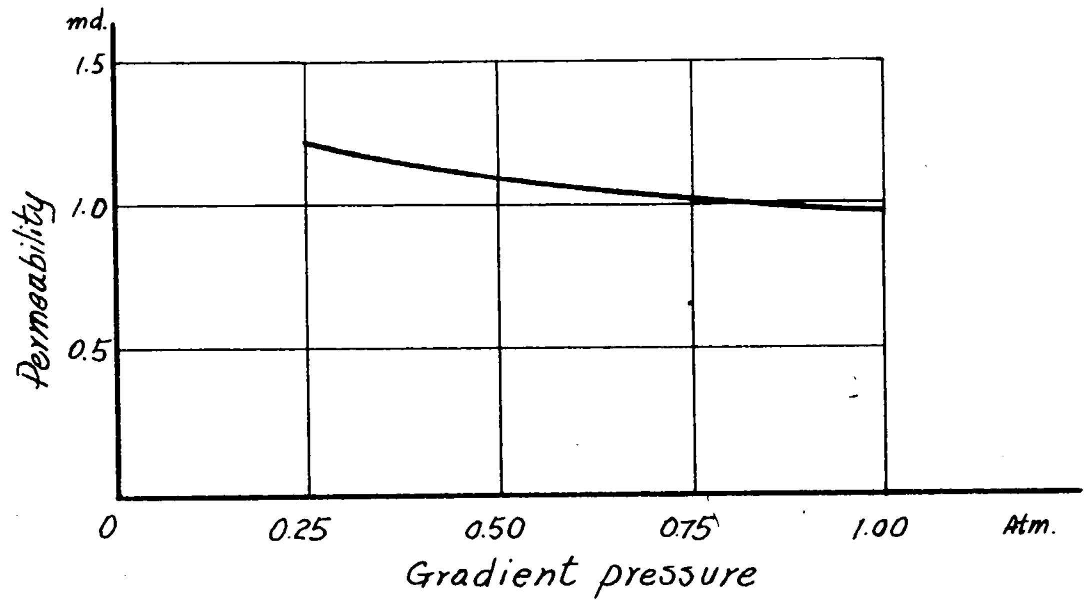


Figure 4. Permeability of coal at Different Pressure gradients

Table 1. Permeabilities of Coal Samples

(O) Samples from Olga Coal Co.

Sample No.	K_1 (md.)	K_2 (md.)	K_3 (md.)
1	0.05	0.03	0.06
2	1.48	0.26	2.08
3	0.53	0.24	0.45
4	0.60	0.21	0.10
5	0.32	0.13	0.79
6	0.20	0.07	0.05
7	0.55	0.35	0.15
8	0.06	0.03	0.23
9	1.60	0.63	4.53
10	0.29	0.12	0.02
11	0.05	0.02	0.02
Average	0.52	0.19	0.77

(U) Samples from U.S. Steel Corp. Mine

Smmple No.	K_1 (md.)	K_2 (md.)	K_3 (md.)
1	6.73	3.85	0.02
2	15.92	8.50	0.10
3	12.11	6.96	6.36
4	9.03	5.24	0.24
5	25.01	8.86	12.32
6	10.00	5.04	0.03
7	1.07	0.54	0.27
8	0.42	0.28	5.98
9	26.45	10.70	0.02
10	9.98	7.25	9.93
11	8.07	0.75	5.54
Average	10.45	5.27	3.71

(P) Samples from Pocahontas Fuel Co. Amonate Mine

Sample No.	K_1 (md.)	K_2 (md.)	K_3 (md.)
1	4.24	0.23	12.86
2	1.00	0.14	16.69
3	2.67	0.84	18.66
4	1.86	0.90	9.96
5	4.65	1.91	12.68
6	8.35	3.38	0.35
7	4.23	1.97	9.10
8	1.22	0.25	2.36
9	0.34	0.23	6.30
10	1.71	0.15	2.21
11	13.40	7.70	3.16
12	2.57	1.51	1.00
Average	3.86	1.60	7.94

(P) Samples from different benches of Amonate Mine

Sample No.	K_1 (md.)		
	a	b	c
1	2.21	3.53	13.30
2	1.43	11.72	4.90
3	2.77	5.93	3.21
4	2.02	16.26	10.40
Average	2.11	9.36	7.95

In Table 1, K_1, K_2 and K_3, represented the permeabilities of the coal samples parallel to the bed, of the wetted coal sample (parallel to the bed), and dry coal samples perpendicular to the bed respectively, and a, b and c represented the upper, middle and lower bench respectively.

(b) The proximate analysis of coal

The proximate analysis of received coal samples is shown in Table 2.

(c) The coal permeability versus the flow rate

For a series of tests, the flow rates could be shown as follows: Figure 5 shows the coal permeability parallel to the bed versus flow rate. Figure 6 shows the coal permeability of wetted samples (parallel to the bed) versus flow rate. Figure 7 shows the coal permeability perpendicular to the bed versus flow rate, and Figure 8 shows the coal permeability parallel to the bed versus flow rate with respect to the different benches. All these figures show that the flow rate is proportional to the permeability of coal.

Table 2. The Proximate Analysis of Coal

Sample Pocahontas No. 4 Seam	Moisture	Volatile Matter	Ash	Fixed Carbon
Olga Coal Co. (O)	0.40%	21.66%	9.03%	68.91%
U.S. Steel Corp. Mine (U)	0.33%	17.54%	16.20%	65.93%
Pocahontas Fuel Co. (P)	0.31%	27.56%	5.04%	67.09%

Ash and Moisture Free Basis

Sample Pocahontas No. 4 Seam	Voaltile Matter	Fixed Carbon
Olga Coal Co. (O)	23.92%	76.08%
U.S. Steel Corp. Mine (U)	21.02%	78.98%
Pocahontas Fuel Co. (P)	29.12%	70.88%

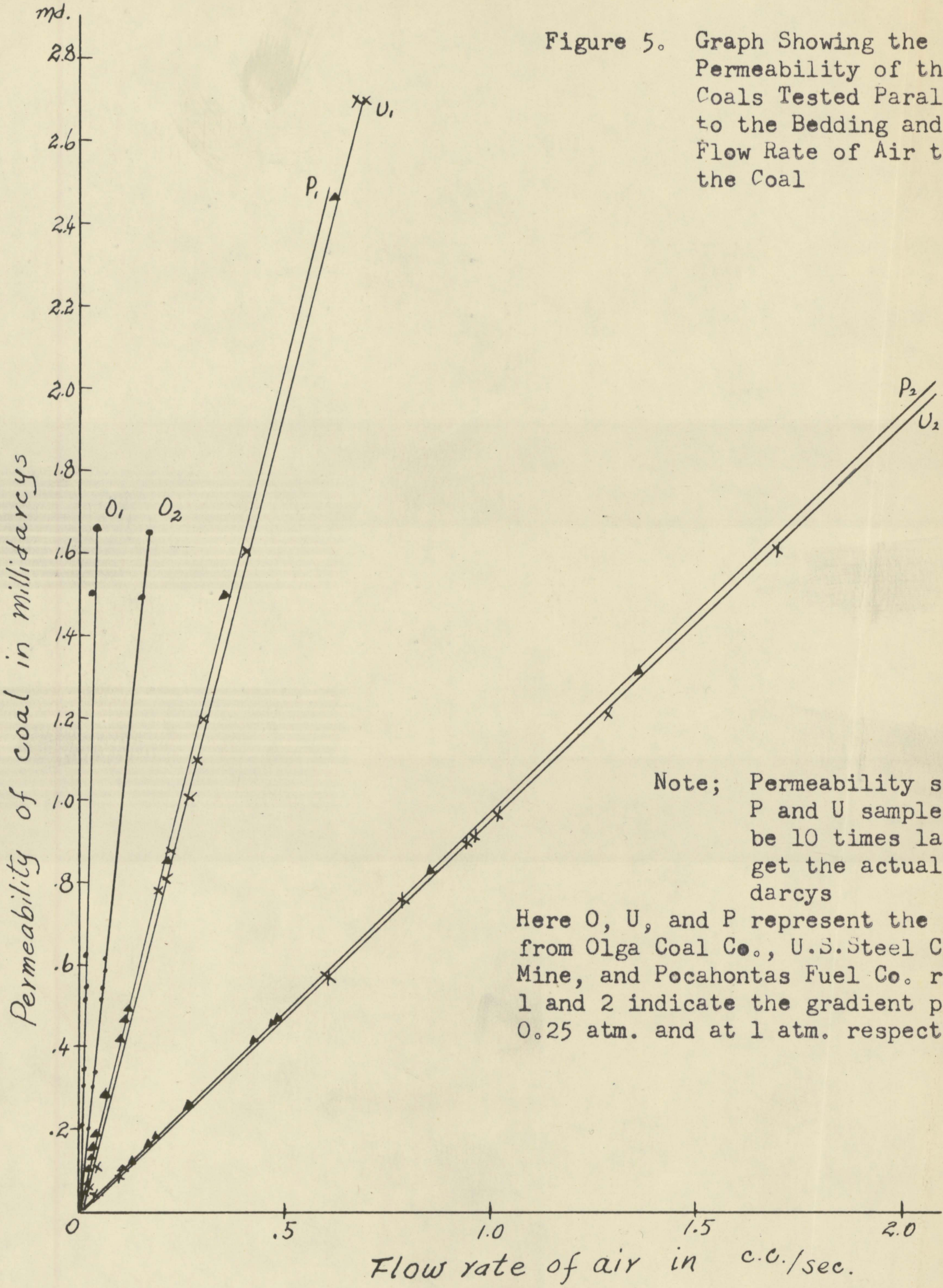
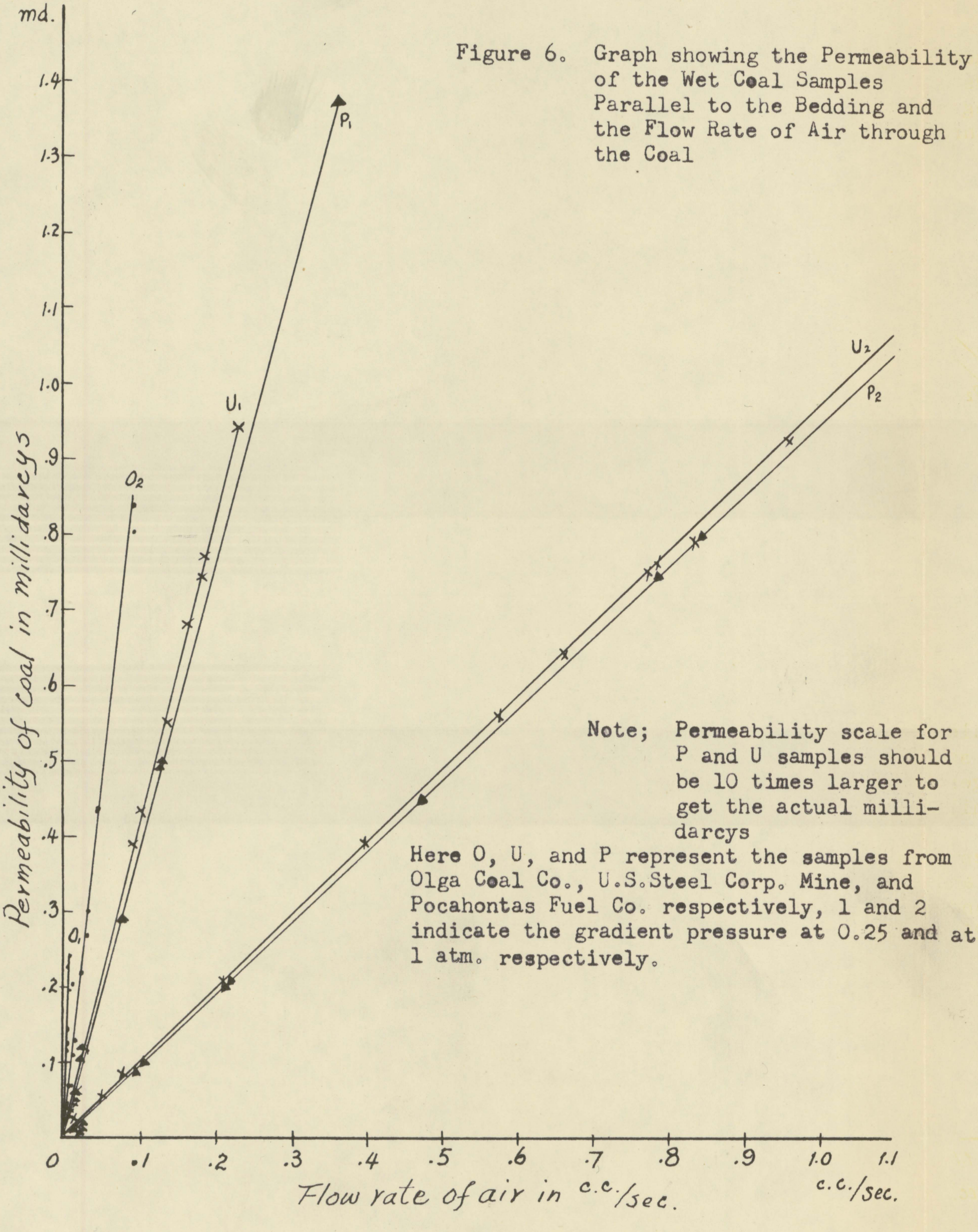


Figure 5. Graph Showing the Permeability of the Coals Tested Parallel to the Bedding and the Flow Rate of Air through the Coal

Note; Permeability scale for P and U samples should be 10 times larger to get the actual millidarcys

Here O, U, and P represent the samples from Olga Coal Co., U.S.Steel Corp. Mine, and Pocahontas Fuel Co. respectively, 1 and 2 indicate the gradient pressure at 0.25 atm. and at 1 atm. respectively.

Figure 6. Graph showing the Permeability of the Wet Coal Samples Parallel to the Bedding and the Flow Rate of Air through the Coal



Note; Permeability scale for P and U samples should be 10 times larger to get the actual millidarcys

Here O, U, and P represent the samples from Olga Coal Co., U.S.Steel Corp. Mine, and Pocahontas Fuel Co. respectively, 1 and 2 indicate the gradient pressure at 0.25 and at 1 atm. respectively.

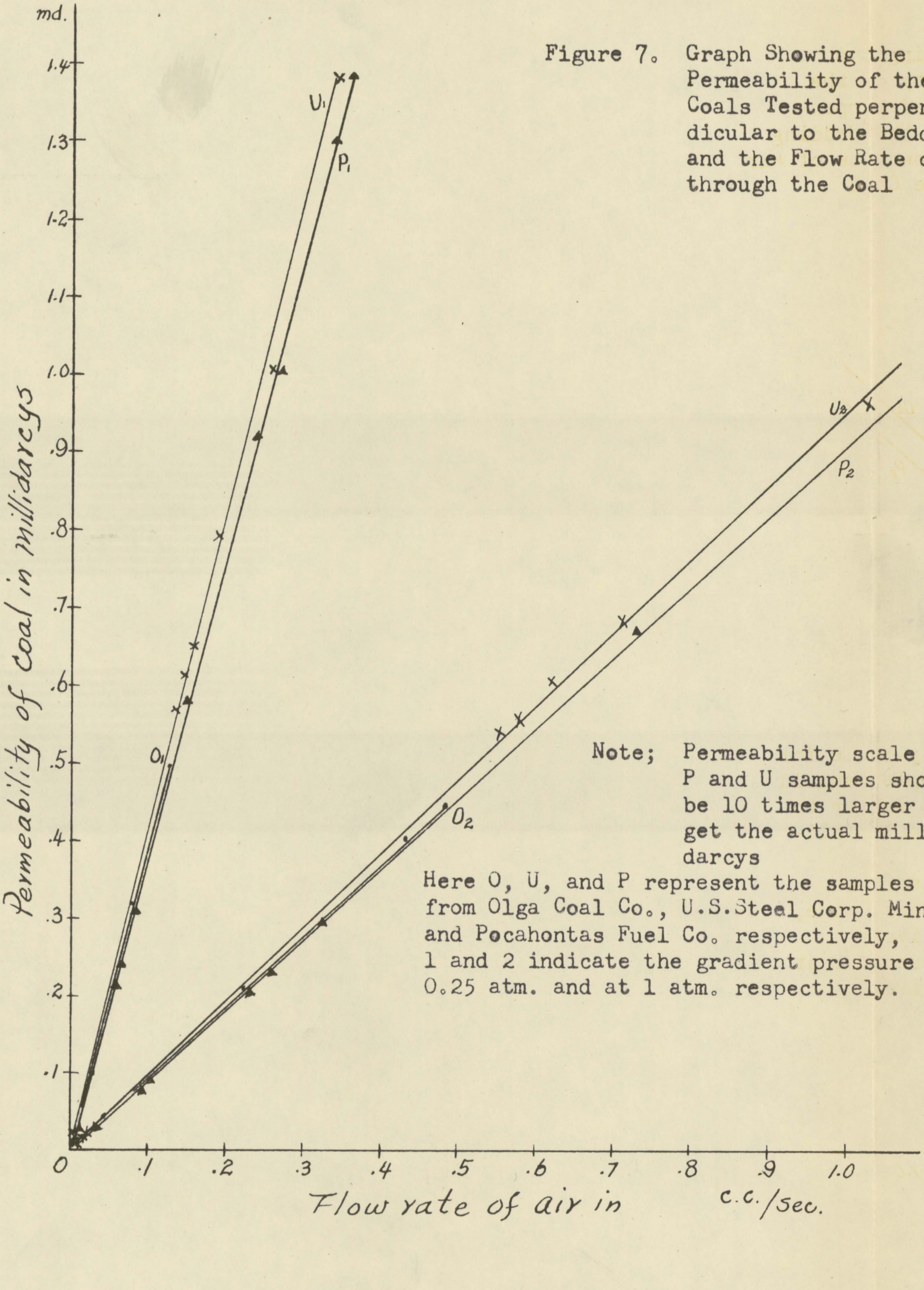


Figure 7. Graph Showing the Permeability of the Coals Tested perpendicular to the Bedding and the Flow Rate of Air through the Coal

Note; Permeability scale for P and U samples should be 10 times larger to get the actual millidarcys

Here O, U, and P represent the samples from Olga Coal Co., U.S.Steel Corp. Mine, and Pocahontas Fuel Co. respectively, 1 and 2 indicate the gradient pressure at 0.25 atm. and at 1 atm. respectively.

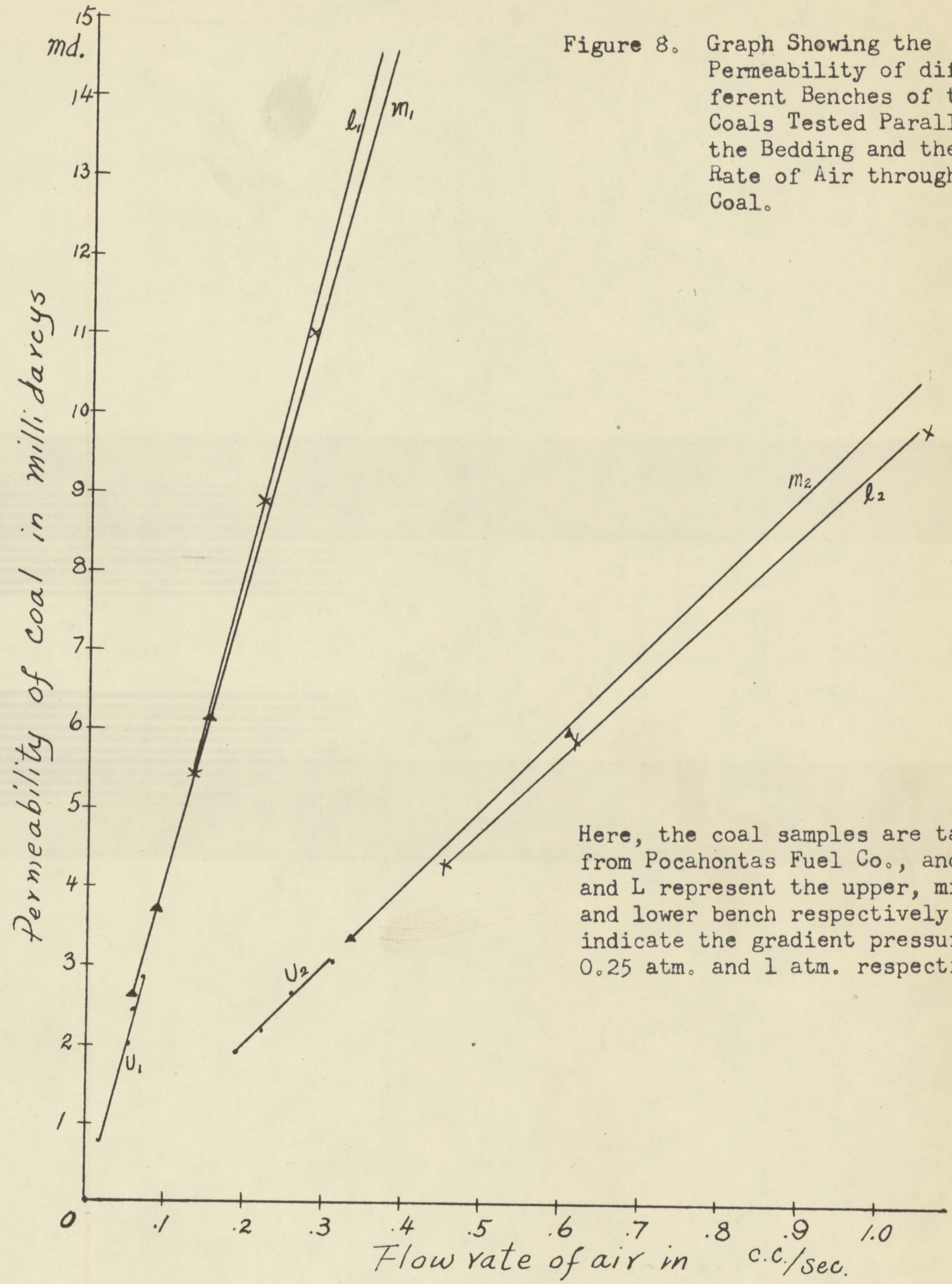


Figure 8. Graph Showing the Permeability of different Benches of the Coals Tested Parallel to the Bedding and the Flow Rate of Air through the Coal.

Here, the coal samples are taken from Pocahontas Fuel Co., and U, M, and L represent the upper, middle, and lower bench respectively, 1 and 2 indicate the gradient pressure at 0.25 atm. and 1 atm. respectively.

COMPARISION OF THE RESULTS OBTAINED

(A) The mean values and the probable errors of the mean

Mean value is defined as the sum of the observations divided by the number of observations. However, this value does not in itself give a clear picture of a distribution. Another type of measure which helps to clarify the shape of the distribution is its probable error which indicates how the observations are spread out from the average, which is measured in the same units as the mean, and which tells the distance to either side of the mean within which half of the mean values, each representing the same number of individual values, would lie. Thus, mean value could be expressed by equation as

$$\bar{X} = \sum x/n \qquad (5)$$

where $\sum x$ indicates the sum of the observations, n indicates the number of observations and $\bar{X}$ is the mean value.

The equation for the probable error is[14]

$$e = (\sum d^2/f)^{\frac{1}{2}} \qquad (6a)$$

$$E = 0.6745\,[\sum d^2/n(n-1)]^{\frac{1}{2}} \qquad (6b)$$

where $\sum d^2$ indicates the sum of the square of the deviations, f indicates the proper value for the appropriate n, and e and E are the probable errors for n less than 30 and more than 30 respectively. The value f for the appropriate n may be tabulated as in Table 3.

From Table 1. and by applying equation (5) and (6a), using the number of observations, the mean values of the coal permeabilities, and the probable errors of the corresponding means were listed in Table 4.

(B) To test significance of difference between two means

When comparing the means of two samples by statistical methods, the "t" distribution test is used. In Smith's work the "t" value is computed according to the equation[14]

$$t = D/Sp\ (\ n_1 \cdot n_2 \ /\ n_1 + n_2\ )^{\frac{1}{2}} \qquad (7)$$

where D is the difference between two sample means, irrespective of sign, Sp is the combined deviation as

$$Sp = (\sum d_1^2 + \sum d_2^2 \ /\ n_1 + n_2 - 2\ )^{\frac{1}{2}}$$

where ($n_1 + n_2 - 2$) is called the number of degree of freedom. The n_1 and n_2 are number of observations in the respective sets. Further, according to the curve for determining significance of the differences as shown in Figure 9, the probability that the difference in question would be exceeded at random, could be found, also the levels of significance could be found at the right side of the Figure, by extending the proper value to entersect the corresponding curve of the degree of freedom.

By using equation (7), the permeability of coal samples has been compared under different conditions and effects, these results are shown in Table 5(a), 5(b), 5(c), 5(d),

Table 3. Values of f

n	f	n	f
2	2.0	12	270
3	9.0	13	320
4	20.4	14	376
5	36.2	15	428
6	56.2	16	488
7	81.7	17	556
8	112	18	622
9	142	19	700
10	178	20	771
11	221		

Table 4. Mean Values of The Coal Permeabilities and Their Probable Errors

Category	n	Means (X) md.	Probable errors ±(e) md.
OK_1	11	0.53	0.12
OK_2	11	0.19	0.03
OK_3	11	0.77	0.29
UK_1	11	10.45	1.79
UK_2	11	5.72	0.76
UK_3	11	3.71	0.96
PK_1	12	3.86	0.75
PK_2	12	1.60	0.44
PK_3	12	7.94	1.33
P_aK_1	4	2.11	0.21
P_bK_1	4	9.36	2.20
P_cK_1	4	7.95	1.80

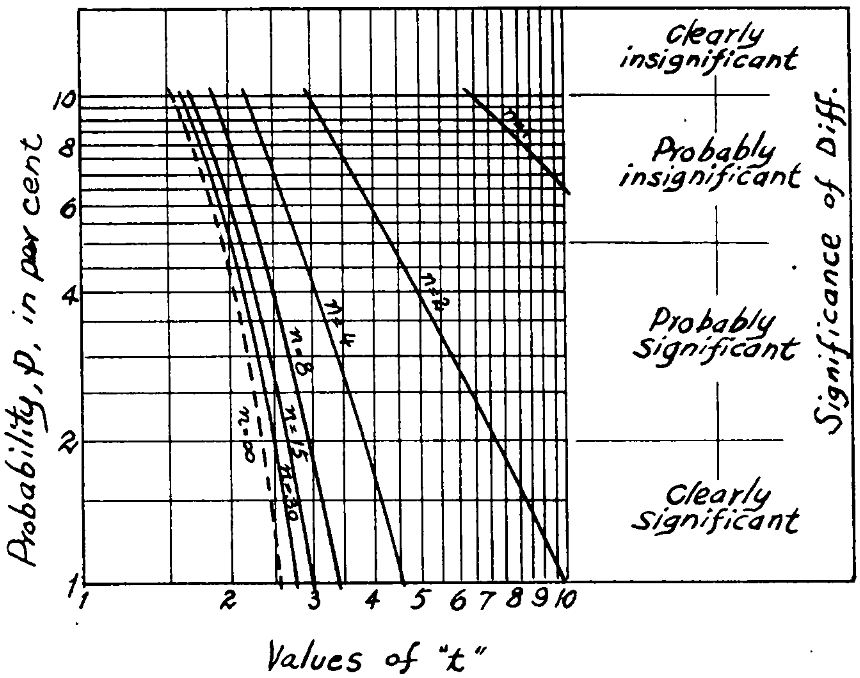


Figure 9. "t" Value Versus Probability
(from reference No. 14)

5(e) and 5(f).

In Table 5(a), it is shown that the permeability of the coal samples when the gas flow is parallel to the bedding has a significant difference or a probable significant difference from place to place.

In Table 5(b), it is shown that the permeability of coal samples when the gas flow is perpendicular to the bedding is either significantly different, probably significantly different, or probably insignificantly different, depending upon the samples being compared. Therefore, considerable variation in this property may be expected at different location in a given bed.

In Table 5(c), it is shown that the permeability of the wet coal samples when the gas flow is parallel to the bedding is significantly different or probably significantly different from place to place. Thus, the probability is high that the permeability of coal differs from place to place in this regard in a given coal bed.

In Table 5(d), it is shown that there is probably a significant difference in coal permeability between the middle bench and the upper bench. On the other hand, however, there is an insignificant difference in the permeability between the middle bench and the lower bench, and there is probably an insignificant difference when the lower bench is compared with the upper bench. Therefore, it may be concluded that considerable variability exists in coal permeability between

Table 5(a). Comparing the permeability parallel to the bedding in samples from different locations.

Samples compared	Difference between means	"t" value	Degree of freedom	Level of significance
U.S. Steel Corp. with Olga Coal Co.	9.93	3.91	20	significant
U.S. Steel Corp. with Pocahontas Fuel Co.	6.59	2.47	21	probably significant
Pocahontas Fuel Co. with Olga Coal Co.	3.34	2.94	21	significant

Table 5(b). Comparing the permeability perpendicular to the bedding in samples from different locations.

Samples compared	Difference between means	"t" value	Degree of freedom	Level of significance
Pocahontas Fuel Co. with U.S. Steel Corp.	4.23	1.84	21	probably insignificant
Pocahontas Fuel Co. with Olga Coal Co.	7.17	3.68	21	significant
U.S. Steel Corp. with Olga Coal Co.	2.94	2.06	20	probably significant

Table 5(c). Comparing the permeability parallel to the bedding in water soaked samples from different locations.

Samples compared	Difference between means	"t" value	Degree of freedom	Level of significance
U.S. Steel Corp. with Olga Coal Co.	5.08	4.73	20	significant
U.S. Steel Corp. with Pocahontas Fuel Co.	3.67	3.00	21	significant
Pocahontas Fuel Co. with Olga Coal Co.	1.14	2.18	21	probably significant

Table 5(d). Comparing the permeability parallel to the bedding in samples from different benches (Pocahontas Fuel Co.)

Samples compared	Difference between means	"t" value	Degree of freedom	Level of significance
Middle Bench with Upper Bench	7.25	2.56	6	probably significant
Middle Bench with Lower Bench	1.41	0.38	6	insignificant
Lower Bench with Upper Bench	5.84	2.47	6	probably insignificant

Table 5(e). Comparing the permeability parallel to the bedding in samples of dry and wet coal from same location

Samples compared	Difference between means	"t" value	Degree of freedom	Level of significance
Olga Coal Co.	0.33	1.91	20	probably insignificant
U.S. Steel Corp.	5.18	1.88	20	probably insignificant
Pocahontas Fuel Co.	2.26	1.73	22	probably insignificant

Table 5(f). Comparing the permeability parallel to the bedding with permeability perpendicular to the bedding in samples from same location.

Samples compared	Difference between means	"t" value	Degree of freedom	Level of significance
Olga Coal Co.	0.25	0.56	20	insignificant
U.S. Steel Corp.	6.74	2.34	20	probably significant
Pocahontas Fuel Co.	4.08	1.93	22	probably insignificant

the different benches of a given bed.

In Table 5(e), on the basis of statistical analysis, it is shown that the permeability of dry coal samples, when the gas flow is parallel to the bedding, is probably insignificantly different to wet coal samples tested on the same basis. However, in every case tested, the individual test gave a lower value of permeability when the sample was wet than when the sample was dry. Therefore, despite the result of statistical analysis, one is inclined to believe that the wet coal will usually have a lower permeability than dry coal when the gas flow is parallel to the coal bedding.

In Table 5(f), it is shown that the permeability of the coal samples, when the gas flow is perpendicular to the bedding, is either insignificantly different or probably insignificantly different or probably significantly different from the permeability of coal samples when the gas flow is parallel to the bedding planes. Therefore, it seems logical to conclude that in many places there is no significant difference in the permeability of coal perpendicular and parallel to the bedding. Although in some areas it may be expected that a significant difference may exist.

SUMMARY AND CONCLUSION

The broad problem of coal bed degasification of which this study is a small part, deserves attention for the following reasons: (1) Mine personnel safety, (2) Economical recovery of the gas. Physically, the gas is liberated in the coal mines became of two conditions. These are: (1) somewhere in the coal bed itself, the gas is under a force or pressure which is larger than atmosphere pressure and which drives the gas toward an opening, and (2) the coal will permit the gas to flow through it. In order to study the interaction of these two conditions, the permeability of coal is of importance.

The permeability of coal may be defined as a measure of the ease with which the gaseous fluid flows through the coal, with a given pressure gradient. The flow rate of the gas is proportional to the permeability of coal. Unfortunately, both in the theoretical and practical aspects, there are so many factors, which affect the permeability of coal, that it is usually necessary to assess its effects in a qualitative way rather than in a quantitative one. For this reason, a simple equation to encompass all the factors needed to determine the coal bed permeability can hardly be developed.

In this study, the equation used for computing the permeability of coal is based on Darcy's Law and certain assumptions. The factors that affect the coal permeability have been briefly discussed, such as: (1) geometrical property of porous media, (2) properties of fluid, (3) adsorption and discharge of gas by coal, (4) overburden pressure, and (5) directional influence. With respect to a coal bed the factors that affect the coal permeability have been discussed, such as; (1) porous overburden and formation of fissures, (2) different locations, (3) different benches, (4) water and gas content in the coal bed, and (5) influence of mining method and cleavages due to mining.

A Ruska gas permeameter is employed to measure the permeability of coal. Careful techniques are necessary on preparing the coal samples, which are very delicate substances especially low volatile bituminous coal, and on operating the gas permeameter. Upon test, the samples are imbedded in metal sleeves with sealing wax before being clamped in the sample holder of the gas permeameter. Further, it is suggested the air be allowed to pass through sample in the gas permeameter for a few minutes before taking any reading.

From the result of experiment, it can be concluded that (1) the permeability of coal differs from place to place, apparently, therefore location should be taken into consideration when an attempt is made to drain the gas from a coal bed; (2) the permeability of coal may or may not differ from bench to bench in the bed at a given location; (3) on the basis of statistical analysis, the permeability of dry coal does not differ significantly from that of wet coal, however, in every measurement made, the permeability of the wet coal samples was lower than that of the dry coal samples when the permeability of the wet coal samples parallel to the coal bedding was determined; and also (4) in many areas, no significant difference in permeability of coal to gas flow parallel-to-the-bedding as compared to gas flow perpendicular-to-the-bedding may be expected. Although in some areas such a difference may exist.

BIBLIOGRAPHY

1. Price, P. H. and Headlee, A. J. W.
" Natural Coal Gas In West Virginia " Bull. Am. Ass. Petro. Geol., V 27, P 529, 1943

2. Lawall, C. E. and Morris, L. M.
" Occurrence And Flow of Gas In Pocahontas No. 4 Coal Bed In Southern West Virginia " Trans. A. I. M. E.,V 108, P 11, 1934

3. Muskat, M.
Physical Principle Of Oil Production McGraw Hill, P 124, 1949

4. Russell, W. L.
Principle Of Petroleum Geology McGraw Hill, P 98, 1951

5. Lambe, T. W.
Soil Testing For Engineers John Wiley & Sons, P 53, 1956

6. Scheidegger
The Physics Of Flow Through Porous Media The MacMillan Co., P 59, 1957

7. Burcik, E. J.
Properties of Petroleum Reservoir Fluid John Wiley & Sons, P 27, 1957

8. Briggs and Sinha
" The Discharge Of Firedamp From Coal " Trans. of Institution of Mining Engineer, London, V 87, P 190, 1933-1934

9. Maas, W.
" The Adsorption Of Methane On Coal And Its Release In A Mine " Sheffield Univ. Mining Magazine P35, 1959

10. Fatt, I. and Davis, D. H.
" Reduction In Permeability With Overburden Pressure " Trans. A. I. M. E., V 195, P 329, 1952

11. Pressler
" Geology And Occurrence Of Oil In Florida " Bull. Am. Ass. Petro. Geol., V 31, P 1851, 1947

12. Chamberlin, R. T.
" Notes On Explosive Mine Gases And Dusts With Special Reference To Explosions In The Monogah, Darr, And Naomi Coal Mines" U.S. Geol. Survey Bull., V 383, P 35, 1909

13. Ruska Gas Permeameter Catalog (No. 1101,)
6121 Hillcroft Ave., Houston 36, Texas

14. Smith, C. M.
" An Investigation of The Friability of Different Coals" Bull. of Univ. of Ill. Engr. Exp. Stat., No. 196, P 39, Nov. 1929

15. Lawall, C. E. and Holland, C. T.
" Some Physical Characteristics of West Virginia Coal" Bull. of W. Va. Univ., Series 37, No. 8-IV, Feb., 1937

16. Moore, E. S.
Coal John Wiley & Sons, P 177, 1950

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A STUDY OF THE FACTORS THAT AFFECT

THE PERMEABILITY OF COAL

by

Shiun Ming Koo

ABSTRACT

The problem of degasification of coal beds is important because it is desirable to reduce the inflammable gas in coal mines as well as to recover economically the gas for use as a fuel. Permeability of coal is defined as a measure of the ease with which a gas flows through coal under a given pressure gradient, and it is of practical importance in the problem of degasification. The factors that affect the permeability of coal are also important in order to develop a more effective way of degasification. This study is concerned with the factors that affect the permeability of coal.

Some of the major factors which affect the permeability of coal are the property of coal, properties of the natural coal gas, physical and chemical correlations between the coal and the gas, overburden pressure, and direction of the gas flow and other factors. In the case of these factors it is usually necessary to assess their effects in a qualitative way rather than in a quantitative one. For

this reason, it would be impossible in the time alloted to this paper to present anything more than a brief discussion of their interrelationships.

By experiment conducted for this thesis, it has been determined that (1) the permeability of coal differs from place to place, (2) the permeability of coal may or may not differ from bench to bench in the bed of a given location, (3) the permeability of dry coal does not differ significantly from that of wet coal, and also (4) in general, no significant difference in permeability was found when the gas flowed parallel to the coal bedding and when it flowed perpendicular to the coal bedding.