Estimation of methane content in Montana coals
by Pamela Elaine Pagel Helmer

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Chemical Engineering
Montana State University

Abstract:
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This was accomplished by measuring the amount of methane adsorbed as a function of pressure in a laboratory apparatus. The in-situ coal seam pressures were then estimated and the quantity of methane calculated. It was estimated that total Montana coal reserve contains 12.8X1013 cubic feet of methane at standard conditions. It was found that the wet coals studied approach 1100 to 1200 ft3/ton at 100 atmospheres.

The surface areas of the coals were analyzed by carbon dioxide adsorption in conjunction with the Dubinin-Polanyi Relationship. The surface areas calculated ranged from 173.1 to 233.6 m2/g. It was found that low pressure, 0 to 6 psia, carbon dioxide adsorption on dry coals could be used to estimate high pressure, 600 psia and higher, methane adsorption on wet coals.

Mercury porosimetry analysis was also done on the coal. It was found to be of very little use in determining the quantity of methane adsorbed because coal is very micro-porous. It would be useful information for determining how easily a coal bed could be degassed because it indicates the number of macropores available for gas flow. The macroporosity of the coals studied varied considerably.

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APPROVAL

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Pamela Elaine Pagel Helmer

This thesis has been read by each member of the thesis committee and has been found to be satisfactory regarding content, English usage, format, citation, bibliographic style, and consistency, and is ready for submission to the College of Graduate Studies.

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Chairperson, Graduate Committee

Approved for the Major Department

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NOMENCLATURE

Dubinin-Polanyi Equation (1)

W	=	Weight Adsorbed
W_o	=	Micropore capacity at saturation
D	=	Constant
P	=	Equilibrium pressure
P_o	=	Saturation pressure

Washburn Equation (2)

γ	=	Liquid surface tension
θ	=	Contact angle
r	=	Pore radius
P	=	Applied pressure

Airey's Empirical Model Equations (3) and (4)

$V(t)$	=	Volume of gas released from a coal sample per mass of coal
t	=	Time
A	=	Initial gas content of a coal sample
t_o	=	Time constant
n	=	An index used in the empirical equation
a	=	Half-thickness of a slab
a_o	=	Mean-sized half-thickness
$W(m)$	=	Fractional weight of coal between size m and m+dm
σ	=	Standard deviation of W(m)
m	=	Parameter

θ = Dimensionless time

θ_o = Dimensionless time

k = The permeability of a homogeneous slab

p = Methane pressure in the solid

p* = Initial methane pressure

s = Volume of gas adsorbed per atmosphere/total volume of coal

μ = Viscosity of methane

$V(\theta)$ = The fraction of methane lost from a slab up to time θ

$f(\theta_o)$ = Total fraction of methane emitted in all size ranges up to time θ_o

Equations (5-10)

V = Volume of pores

n = Number of pores

r = Pore radius

l = Pore length

$D_V(r)$ = Volume pore-size distribution function

S = Surface area

Ideal gas law and Benedict-Webb-Rubin Equation (11)

R = Universal gas constant

n = Moles

V = Volume

P = Pressure

A_o = Benedict-Webb-Rubin (BWR) constant

B_o = BWR constant

C_o = BWR constant

a = BWR constant

b = BWR constant

c = BWR constant

α = BWR constant

γ = BWR constant

ρ = BWR constant

Equation (12)

N = Avogadro's number

σ = Cross-sectional area of the adsorbate

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The purpose of this research was to estimate the methane content of Montana coals. The coals examined were taken from Big Horn and Powder River counties; two were subbituminous and one was lignite.

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INTRODUCTION

It has been known for centuries that methane is held in coal. The quantity is so large that coal-beds must be degassed for days, weeks, even years before safe underground mining can be accomplished. The recent high energy prices have induced the consideration of the recovery of the methane (natural gas) in coal beds before they are mined. The gas removed from coal beds is usually greater than 90 percent methane [1]. Currently, the recovery technology is limited, but it is being continually improved to make natural gas production from coal beds more economical. Estimates of coal-bed methane resources in the United States range from 200 to 800 trillion cubic feet [1,2,3,4]. This amount is equal to or greater than the proved and currently recoverable reserves of natural gas in the United States. Montana does not have any estimates of the natural gas contained in its vast coal resources, although the amounts and types of coal have been estimated. The goal of this research was to estimate the methane content of various Montana coals. The methane capacity at various pressures was determined for given coals directly by an adsorption apparatus.

Carbon dioxide adsorption at 273 Kelvin was also performed to determine surface areas, and mercury penetration was used to determine pore size distributions. The surface area and the pore size distribution were examined in conjunction with the methane adsorbed. This was done to determine if either could be used to calculate the capacity of methane in any given coal. Together all this information could be used to estimate methane resources in Montana coals.

LITERATURE SEARCH

The Coal-Methane Relationship

Coal has the ability to adsorb gases, especially methane, carbon dioxide and to a limited extent nitrogen. Adsorption is usually a gas-solid or liquid-solid interaction. In general, adsorption involves the accumulation of molecules at a gas-solid interface. The difference between adsorption and absorption is that absorption involves two phases dispersing in one another rather than accumulation of one phase on the surface of another. Adsorption allows a gas to be held more closely to a solid surface. This allows more of a gas to occupy a given space. There are two types of adsorption, physical and chemical. The exact nature of the coal-gas bond is not yet known, but it is believed that physisorption [4], not chemisorption, is the predominant mechanism. Physical adsorption is indicated from the activation energies and the short equilibrium times required a desorb a coal bed. Also, methane and coal are fairly non-reactive. Gunther [5] gives a comprehensive discussion of the coal-methane bond.

Experimental Techniques for Measuring Methane Content in Coals

There are many techniques that have been used to determine the quantity of methane available in coal. The earliest technique used was the Direct Method. It was developed by Bertard, Bruyet, and Gunther [6] in France. The direct method involves volumetrically measuring methane as it desorbs, beginning when the coal is removed from the ground. Bertard et al. only used this technique on coal taken from a working face using horizontal bore holes. Kissell, McCulloch and Elder [7] applied the technique to virgin coal by using vertical bore holes. They also included an estimate for the gas lost from the time the coal

was cut until it reached the surface and could be sealed in a container. Smith and Williams [4] developed a variation of direct method for determining methane content. They based their technique on desorption of drill cuttings called chip-desorption. The advantage of this technique was that extensive coring was not required and sampling could occur as part of normal drilling operations. Because the chips used were small, 2 to 8 millimeters, an estimated 5 to 50 percent of the original methane was lost during collection. A model was developed to account for the lost gas.

Because of the inconvenience of working in the field Hofer, Bayer, and Anderson [8] developed a laboratory procedure to measure adsorption and desorption. They took a coal sample and put it in a calibrated volume which was evacuated at 100°C. The sample was then weighed. Next, known quantities of methane were allowed to flood the system up to a given constant pressure. As adsorption occurred, more methane was added to maintain the pressure. Adsorption rates as well as ultimate volume were recorded. The procedure was reversed to determine if desorption and adsorption rates and volumes were similar. They were found to be almost identical. Good comparison between direct and laboratory methods was also found.

Another laboratory technique was developed by Daines [9]. This technique involved a weighing method to determine adsorption. The basic procedure was to place a sample in a weighed capsule which was evaucated and reweighed. Methane was then admitted to the sample, and after allowing equilibrium pressure to be attained the capsule was weighed again. This procedure was repeated by increasing the equilibrium pressure. To determine the quantity of methane compressed in the spaces surrounding the coal sample, the experiment was repeated using a non-adsorbing solid of the same volume as the coal.

Surface Area

The earliest attempts to determine coal surface area were done by Anderson et al. [10] using heat-of-wetting techniques with water and methanol. The first gas adsorption attempted used nitrogen at 77 K; this data was analyzed by the Brunauer, Emmett, and Teller (BET) Method. It is now generally agreed that nitrogen adsorption at 77 K does not work [11,12,13]. Lamond and Marsh [11] reasoned that the pores are only slightly larger than the nitrogen molecules, thus, nitrogen at 77 K fills the pores at very low relative vapor pressures. This results in reversible capillary condensation before the apparent monolayer capacity is reached.

Because it was believed that the problem in measurement was caused by the low temperature conditions, gas adsorption at the highest possible temperature was investigated. Walker and Kini [12] used several methods to determine coal surface area. They did BET analysis from adsorption isotherms of nitrogen at 77 K, krypton at 195 K, xenon 273 K and carbon dioxide at 195 K and 298 K. They concluded that carbon dioxide at 298 K gave the best measure of the total surface area. The use of BET analysis on carbon dioxide at 273 K to 298 K required low relative pressure, 0.-0.35 P_o/P. Relative pressure is the saturation pressure divided by the operating pressure. For carbon dioxide the saturation pressure is 60.8 atmospheres at the operating temperature. In order to get low relative pressures a high operating pressure is required. Lamond and March [11] proposed the use of the Dubinin-Polanyi (D-P) equation because it could be used at low absolute pressure. Walker and Patel compared BET to D-P and found excellent agreement between the two. Due to the excellent agreement with other techniques [13,14,15,16] the D-P method is currently recommended. The Dubinin-Polanyi equation is:

$$\mathrm{Log}(W) = \mathrm{Log}(W_o) - (D)\mathrm{Log}^2(P_o/P) \qquad (1)$$

where D = Constant

P = Equilibrium Pressure

P_o = Saturation Pressure

W = Amount Adsorbed

W_o = Micropore Capacity

A plot of Log(W) versus $Log^2 (P_o/P)$ is essentially a straight line that can be extrapolated to saturation (i.e., $P/P_o = 1$) to get the micropore capacity, W_o. Then by using the molecular area of carbon dioxide the surface area can be calculated. The generally used surface area per molecule of carbon dioxide is 0.253 nm^2 [13,17].

Coal Density

There are three kinds of coal density; true density, particle density, and apparent density. Only apparent density is of interest for this research.

Apparent density depends on particle size, pore size distribution, molecular size of the fluid, degree of interaction of the fluid with the coal (like swelling and surface effects), and time allowed for penetration. Nelson, Mahajan, and Walker [18] measured densities of coals by displacement of methanol, benzene, and tetralin at 298 K. They found that the densities decreased with increasing molecular size. They also observed that tetralin caused the coal to swell but that the densities were probably fairly accurate due to the inability of the large tetralin molecule to enter the pore structure.

Mercury Porosimetry

Mercury porosimetry can be used to determine the porous properties of a solid. There are several variables upon which mercury porosimetry is dependent, the most important being wetting. Wetting is described as the affinity of a liquid for a solid surface. A liquid that spreads spontaneously along a solid surface is said to wet the surface. A liquid that

forms drops and appears spherical is said to be nonwetting. The contact angle between the liquid and solid surface can be measured to determine if a liquid will be wetting or nonwetting. A liquid with an angle greater than 90 degrees is nonwetting while, a liquid with an angle less than 90 degrees is wetting. Mercury is used to determine porosity properties because it exhibits a contact angle of greater than 90 degrees with more solids than any other conveniently available [19].

Washburn [20] derived the operating equation for mercury porosimetry.

$$Pr = -2\gamma\cos\theta \tag{2}$$

where P = applied pressure

r = pore radius

γ = liquid surface tension

θ = contact angle

The surface tension and contact angle are assumed to be constant; for mercury the surface tension and contact angle for most solid surfaces are 484 erg/cm^3 and 140 degrees, respectively [19]. Since the contact angle, θ, is greater than 90 degrees, an exerior force must be applied to drive the mercury in to the pores of a solid. The Washburn equation is used to determine the radius of the pores that mercury will enter at a given pressure. Most porosimeters can only go up to 60,000 psi, meaning the mercury only penetrates pores having a radius greater than 1.8 nm. Often the porous material is crushed at these pressures.

The raw data obtained from a mercury porosimeter is pressure versus volume of mercury intruded into the pores. From this data radius versus volume, pore-size distribution, and surface area can be determined. Mercury porosimetry, in conjunction with helium, has been used considerably in coal studies to determine pore volume distribution. Gan, Nandi, and Walker [21] used nitrogen adsorption along with mercury and helium densities to classify coal. They state that mercury intrusion at 30,000 psi estimates the pore volume for all pores greater than 30 nm in diameter, nitrogen estimates the volume of pores between

1.2 and 30 nm and helium estimates the volume of pores smaller than 1.2 nm in diameter. It has been shown by several investigators [13,16,21,22,23,24] that most of the pores in coal are 30 nm or less in diameter. This is particularly true for coals with more than 75 percent carbon. Because of the microporosity of coal, the usefulness of mercury penetration tends to be fairly limited. Also, Spitzer, Debelak, and Schrodt [24] determined that the compressibility of coal at high pressure tends to alter the pore structure of coal causing mercury penetration results to be artificial.

Desorption Kinetics

Degassing an adsorbed gas, such as removing methane from coal, requires reduction of the hydrostatic pressure and artificial fracturing the coal to recover trapped gas. Most coal beds are water saturated so the water must be pumped out to reduce the pressure. Artificial fracturing is accomplished by hydraulic stimulation. Usually water carrying sand is injected into a seam. The water is then pumped out leaving some of the sand trapped in the fractures to brace them open so the gas can flow out. Most coal contains vertical fractures called face cleats, which are fairly predominant and continuous. Most fractures created by hydraulic stimulation follow the direction of the face cleats. A more desirable result would be fractures that intersect the face cleats, i.e., horizontal fractures. The Gas Research Institute [1] is currently trying to design reliable, predictable methods for fracturing coal seams.

Airey [25] developed an empirical equation to predict the volumetric desorption of methane from coal over time. The correlation agrees with considerable accuracy to experimental results. The equation was developed from the following observations.

1. The initial rate of methane release is very rapid, it is regarded as infinite,

$$dV(t)/dt \rightarrow \infty \quad \text{as} \quad t \rightarrow 0$$

2. V(t) tends to a constant as the time t tends to infinity,

$$V(t) \rightarrow A \text{ as } t \rightarrow \infty$$

3. V(t) for any finite time is greater for small coal samples than for large coal samples, all other factors being equal.
4. V(t) always increases with time, and dV(t)/d(t) decreases with time.

The equation that satisfies each of these is:

$$V(t) = A[1 - \exp (t/t_o)^{-n}] \quad \text{for } 1 > n > 0 \tag{3}$$

where V(t) = Volume of gas released from a coal sample per mass of coal

A = Initial gas content of a coal sample

t = Time after start of desorption

t_o = A time constant

n = An empirical constant

Airey [25] found that a good value for n is 1/3. The coals to which he applied the equation all had values of n = 0.31 ± 0.04, but since V(t) is not critically dependent on n, a value of 1/3 would be acceptable. Other important conclusions include t_o varying considerably with size and to some extent with initial methane pressure, but not with moisture content. Approximate values for t_o are 10 minutes for 200 BS mesh and 200 hours for 1/4 to 1/2 inch. The total methane content of the coal, A, is also a function of moisture content and the initial methane pressure.

Bertard, Bruyet, and Gunther [6] developed a method for the determination of desorbable gas concentration of coal. They concluded that the desorption rate will be practically independent of size if the coal is larger than one millimeter. However, when the size drops below one millimeter the desorption rate becomes inversely proportional to the size of the particles. They used a constant diffusion coefficient for methane of 10^{-10} cm^2/sec for all coals. Later studies [4] indicate that a constant diffusion coefficient is not acceptable. Hofer, Bayer, and Anderson [8] also conclude that larger coals desorb much

slower than smaller coals. Their results show an eightfold increase in the rate of adsorption/desorption as the particle size decreases from 6-8 to 270-235 mesh per inch.

Airey [25] did further investigation into gas flow in coal. First, he looked at a theory based on flow through a homogeneous solid. Upon comparison with experimental results it was found to be a poor model. Airey concluded that the major disagreement between the homogeneous solid model and the actual coal was that the model assumed uniform permeability. Actually, coal has cracks of all sizes, so a model was developed to take this into account. The assumed size distribution of broken coal was the log-normal distribution [26]. The model was developed as follows:

If the half-thickness of the coal is a, and the half-thickness of the mean-sized slab is a_o, then a parameter m is defined by,

$$m = \ln(a/a_o)$$

or

$$a = a_o \exp(m)$$

Let W(m) be the fractional weight of coal between size m and m+dm. Also, let σ equal the standard deviation, then

$$W(m)dm = 1/\sigma(2\pi)^{1/2} \exp(-m^2/2\sigma^2)dm$$

Next

$$\theta = kp^*t/s\mu a^2$$

and defining

$$\theta_o = kp^*t/s\mu a_o^2$$

then

$$\theta = \theta_o \exp(-2m)$$

and

$$V(\theta) = V(\theta_o \exp(-2m))$$

Where θ and θ_o are dimensionless time, t is time, k is the permeability of a homogeneous slab, s is the volume of gas adsorbed per atmosphere/total volume of coal, and μ is the viscosity of methane. The methane emitted in the size range dm equals the product of the fraction of methane lost in this size range and the fractional weight of coal in this size range, or,

$$\text{methane emitted} = V(\theta_o \exp(-2m))W(m)dm$$

If $f(\theta_o)$ = total fraction of methane emitted in all size ranges up to time θ_o

$$f(\theta_o) = \int_{-\infty}^{+\infty} V(\theta_o \exp(-2))W(m)dm$$

or

$$f(\theta_o) = 1/\sigma(2\pi)^{1/2} \int_{m=-\infty}^{m=+\infty} V(\theta_o \exp(-2m))\exp(-m^2/2\sigma^2)dm \qquad (4)$$

so $f(\theta_o)$ is a function of σ and θ_o. Integration is performed numerically, by the method of Simpson's Rule.

Comparison of this model with experimental results using $\sigma = 2.5$, n = 1/2 are acceptable. The agreement is good over longer times, but for shorter times there is some deviation. Possibly better results would be available if a more comprehensive size distribution were used in the model.

Montana Coal Reserves

Coal is Montana's largest known potential mineral resource. Two-thirds of the state is underlain by relatively young sedimentary rock which was formed during the Carboniferous and Cretaceous Periods of earth history. The coal is in significant quantities and it is located close enough to the surface to be mined using present day technologies [27]. Montana has three kinds of coal, bituminous, subbituminous, and lignite. The estimated reserves are 2,362,610,000; 132,151,060,000; and 87,533,270,000 short tons, respectively [28]. This is estimated to be 13 to 15 percent of the total national reserve. Figure 1 is a

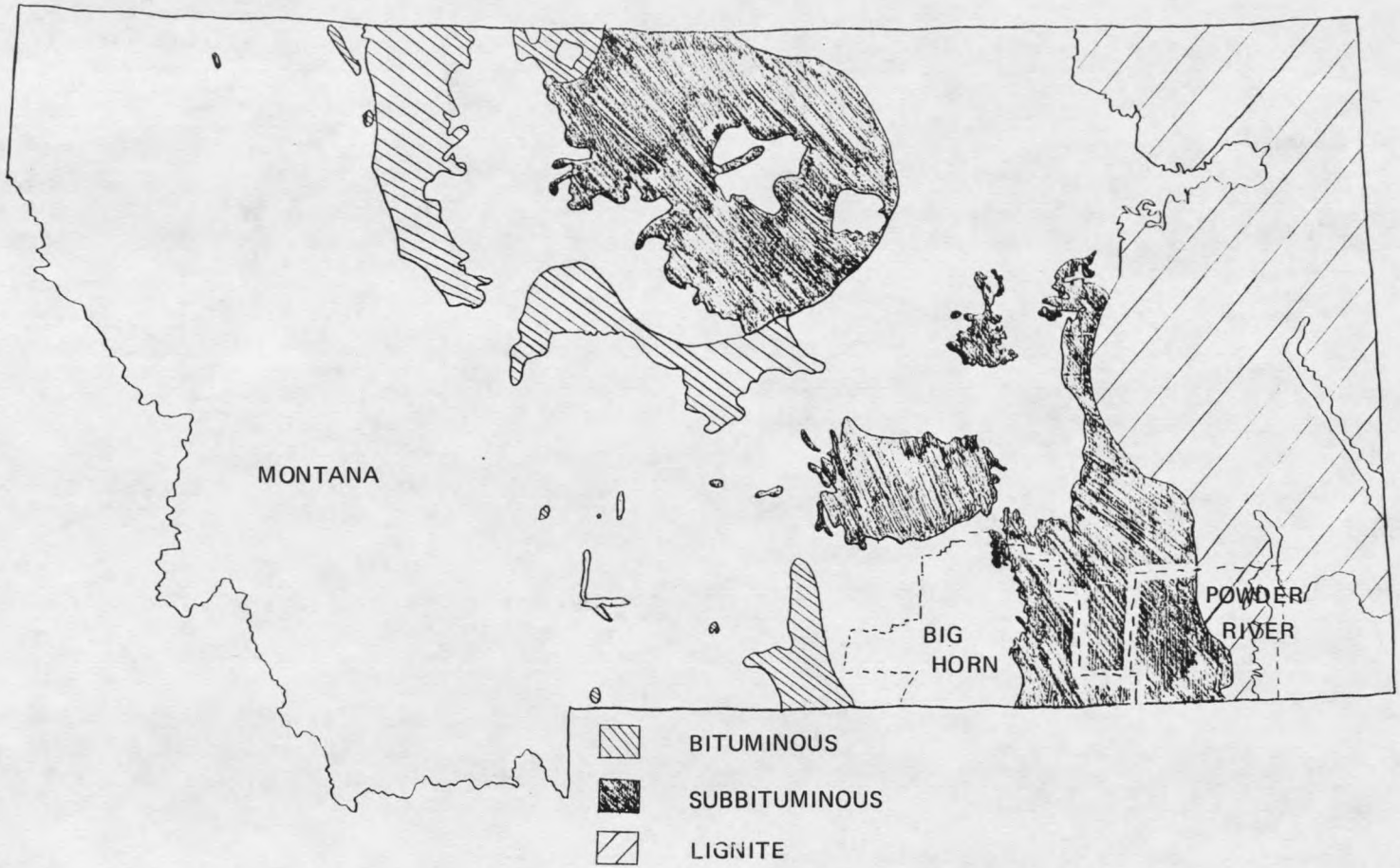

Figure 1. Montana coal reserves.

map showing the location and type of coal found throughout the state. Powder River and Big Horn counties have been identified because the coals being studied in this research are from these areas. Coal samples E83-20 and E83-28 are from Big Horn County, they are subbituminous. Coal sample E83-24 is from Powder River County, it appears to be lignite. The coal samples studied were acquired from the Montana Bureau of Mines and Geology in Butte, Montana.

EXPERIMENTAL

There were three independent systems used in this work; a methane adsorption apparatus, a carbon dioxide adsorption apparatus, and a mercury penetration porosimeter. Each will be discussed separately. Experimental techniques used to determine density, ultimate analysis, percent ash and percent moisture will also be described.

Equipment and Procedure

Methane Adsorption Apparatus

Equipment. The equipment utilized to determine methane adsorption on coal is shown in Figure 2. It consists of a 99.9% pure methane bottle, two volumetrically calibrated tanks, four valves, a vacuum pump, a cold finger and necessary pressure tubing. Tank 1 is calibrated to be 1.220 liters and tank 2 plus the cold finger and connecting tubing are 0.186 liters. Tank 2 is accessible through the top to allow multiple coal samples to be analyzed. A wire sample basket is used to hold the coal. Both of the calibrated tanks are connected to pressure and temperature indicators. The first tank has a Marshalltown test gauge with capability up to 1500 psig, while the second tank is connected to a Validyne Pressure Transducer capable of up to 3600 psia. Due to other limitations of the system the highest pressure utilized is 2000 psia. The thermocouples are connected to a Cole Parmer Model 8530 temperature indicator. The system is operated at ambient temperature so these temperatures are always the same.

Procedure. Experimental analysis by the methane adsorption apparatus described above is accomplished by the following procedure. First, the coal is crushed using a mortar and pestle to a diameter of 1/8 inch or less. Next, the coal is placed in an oven at 110°C

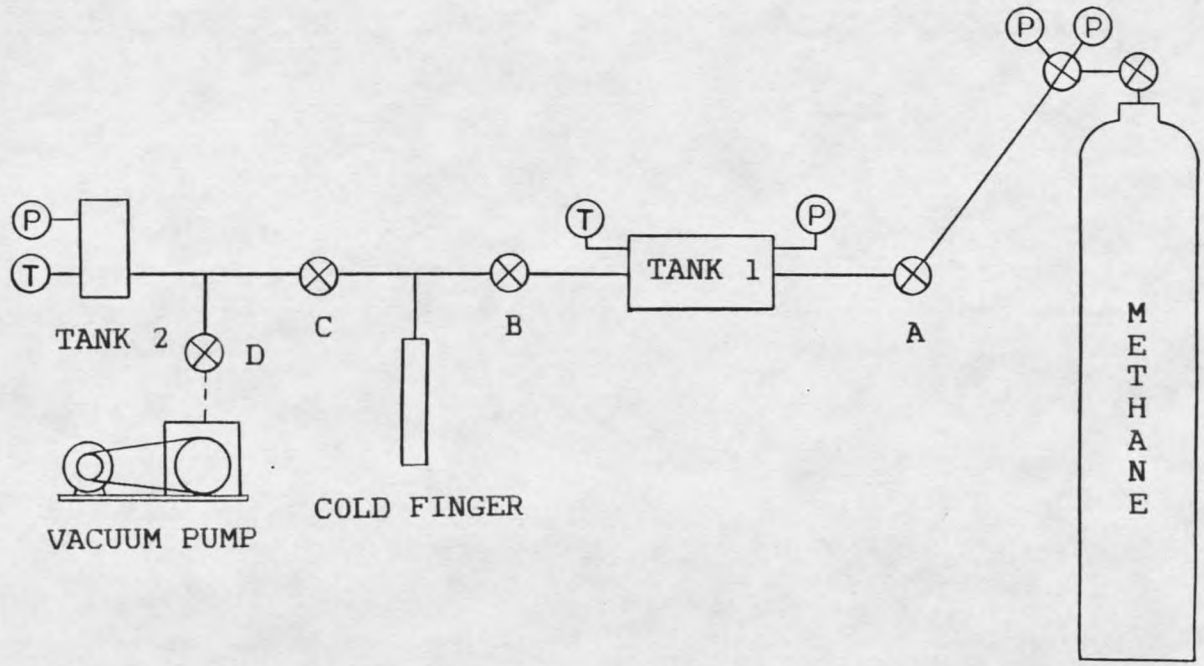

Figure 2. Methane adsorption apparatus.

for 24 hours if the coal is to be dried before analysis. Both wet and dry coals can be analyzed. Once crushed, and dried if required, the coal is put in a weighed sample basket which is then reweighed. Now the coal is loaded into tank 2 and the tank is closed. The entire system is now evacuated for one hour. Next valves B, C, and D are closed and tank 1 is filled with methane from the bottle until a desired pressure is reached. Now valve A is closed and the temperature and pressure of tank 1 are recorded. Next, valve B is opened and the cold finger is immersed in liquid nitrogen until the pressure of tank 1 is zero. Now valve B is closed, valve C is opened, and the liquid nitrogen is removed. Now the methane is revaporized and allowed to come to equilibrium temperature and pressure, this takes approximately 10 to 15 hours. The temperature and pressure of tank 2 are now recorded. This procedure is repeated for one sample until a pressure of approximately 1800 psia in tank 2 is reached. Six runs are usually done on each sample.

Carbon Dioxide Adsorption Apparatus

Equipment. The gas adsorption apparatus is shown in Figure 3. It is comprised of a gas bottle, valves, a mercury manometer, a vacuum pump, a vacuum gauge, an electrobalance, and appropriate plumbing.

Procedure. The sample is crushed in a mortar and pestle to a diameter of 1/8 inch or less. The sample is then put in an oven at 110°C for 24 hours. Next, the sample is loaded onto a pan hanging from the electrobalance and the tare is adjusted. The system is then sealed and evacuated to below 10^{-3} torr. Carbon dioxide is now bled into the system from the gas bottle. The system is allowed to equilibrate and the weight gain is recorded. Several incremental pressures below one atmosphere are typically used.

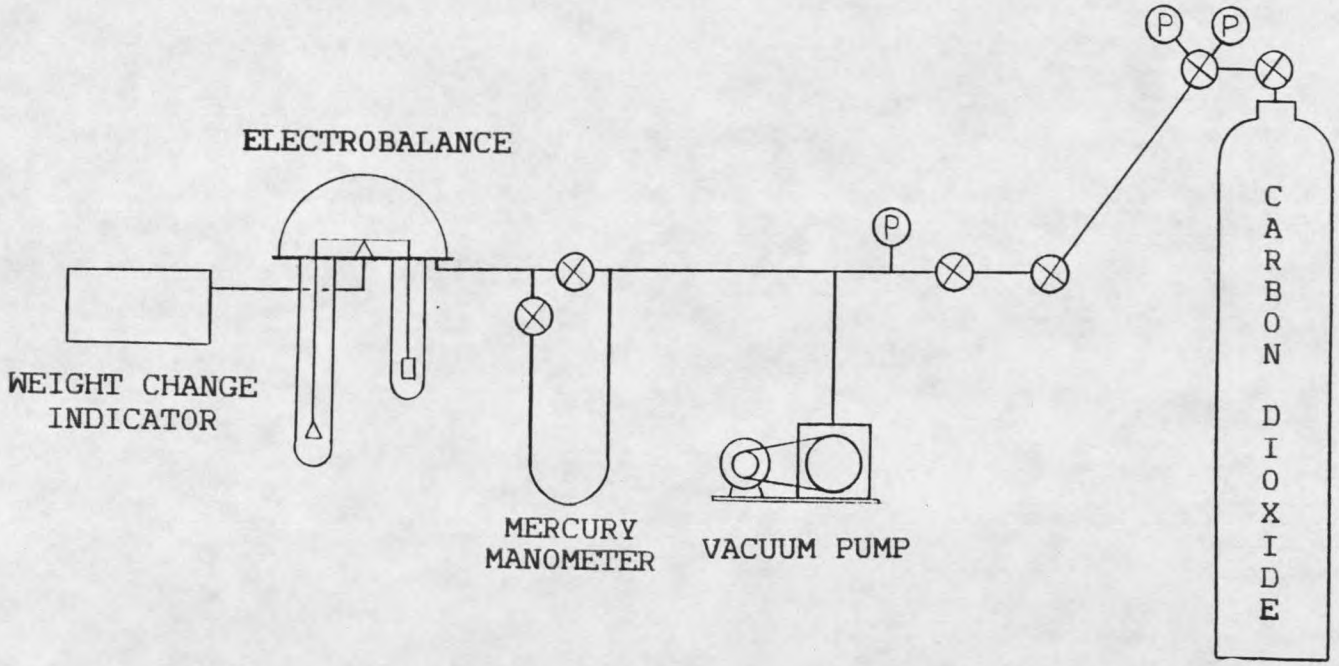

Figure 3. Carbon dioxide adsorption apparatus.

Mercury Penetration Porosimetry

Equipment. A mercury porosimeter consists of a vacuum pump and gauge, a calibrated sample cell, a device to generate pressure, a pressure indicator, a mercury penetration indicator, mercury and appropriate plumbing. The common mercury penetration indicator is a metal probe that enters the sample cell until it meets the mercury, completing an electrical circuit. The depth of penetration indicates the volume of mercury that has penetrated the sample pores.

Procedure. A small weighed sample is placed into the sample cell, which is then loaded into the sample chamber. The chamber is evacuated and then flooded with mercury, the mercury completely surrounds the sample inside the sample cell. The excess mercury is drained away and the initial probe penetration is recorded. The pressure is incrementally increased and corresponding probe penetration is recorded. This procedure is continued until the ultimate pressure available has been reached. Most porosimeters go up to at least 30,000 psi, some go up to 60,000 psi.

Density

Equipment. The density of the coal samples is found by using volumetric techniques. The equipment consists of a scale, a graduated pipet, and a graduated cylinder. The operating fluid is meta-xylene. A fluid with a large molecular structure was chosen because only the apparent density of the solid was desired.

Procedure. The process begins by weighing the graduated cylinder. The cylinder is then filled with coal and reweighed. Next, the graduated pipet is used to put a known volume of meta-xylene in the graduated cylinder with the coal. The meta-xylene must completely cover the coal. The difference between the reading of the graduated cylinder and the volume of meta-xylene added is the volume displaced by the weighed coal sample.

Ashing and Moisture Content

Equipment. The equipment used for determining percent ash and percent moisture is basically the same. It consists of a mortar and pestle, a crucible, a scale, a temperature indicator, and an oven.

Procedure. The ashing procedure begins with heating an empty crucible up to the temperature that the ashing will be performed at, for coal 550 to 750°C is used. Next, the crucible is cooled, weighed, and coal is added. The coal and crucible are now weighed together and placed in the oven when it is still cool. The oven is then heated slowly to the desired temperature, which is then maintained for four to six hours. At this time the crucibles with the ash are weighed. The percent ash is calculated by dividing the weight of the ash by weight of the original coal put into the crucible.

The procedure to calculate percent moisture is similar. A crucible is weighed, filled with coal and reweighed. Then it is put into a constant temperature oven approximately 110°C for 24 hours. At this time the crucible and coal are reweighed. The percent moisture is the final coal weight divided by the initial coal weight.

Ultimate Analysis

Equipment. The ultimate analysis is performed using an Elemental Analyzed Model 1106, Carlo Erba Strumentazione.

Procedure. The basic procedure begins with placing 0.5 to 1.5 milligrams of coal in a lightweight tin container. The container is then dropped at preset intervals of time into a vertical quartz tube. The tube is maintained at 1030°C under a constant flow of helium. When the samples are introduced the helium is enriched with oxygen, flash combustion takes place. Complete quantitative combustion is then achieved by passing the mixture of combustion gases over Cr_2O_3. The mixture of combustion gases is then passed over copper

at 650°C to remove the excess oxygen and to reduce oxides of nitrogen to nitrogen. It then passes through a chromatographic column of Porapak QS heated to approximately 100°C. The individual components are then separated and eluted as N_2-CO_2-H_2O. They are measured by a thermal conductivity detector, whose signal feeds a potentiometric recorder and in parallel an intergrator with digital printout. The instrument is calibrated by combustion of standard compounds.

Calculational Procedures

Mercury Penetration Porosimeter

The raw data collected from a mercury porosimeter is pressure versus volume of mercury intruded into the pores of a sample. Figure 4 is an example of porosimeter data for coal. From this data radius versus volume, pore size distribution, and surface area can be calculated.

Calculation of radius versus volume consists of converting the pressure to radius by using Equation 2, the Washburn Equation, and plotting against the corresponding volume. When using the Washburn Equation, the surface tension, γ, and the contact angle, θ, are assumed constant. In this case γ equals 484 erg/cm^3; while θ equals 140 degrees. After proper unit conversions the equation reduces to

$$r = 106.7/P$$

where r is in microns and P is in psia. Figure 5 is an example of a radius versus volume curve.

Calculation of the pore-size distribution begins by assuming a cylindrical pore structure. When the pore radius is changed from r to r – dr the corresponding decremental change in the pore volume is

$$dV = -2n\pi rldr \qquad (5)$$

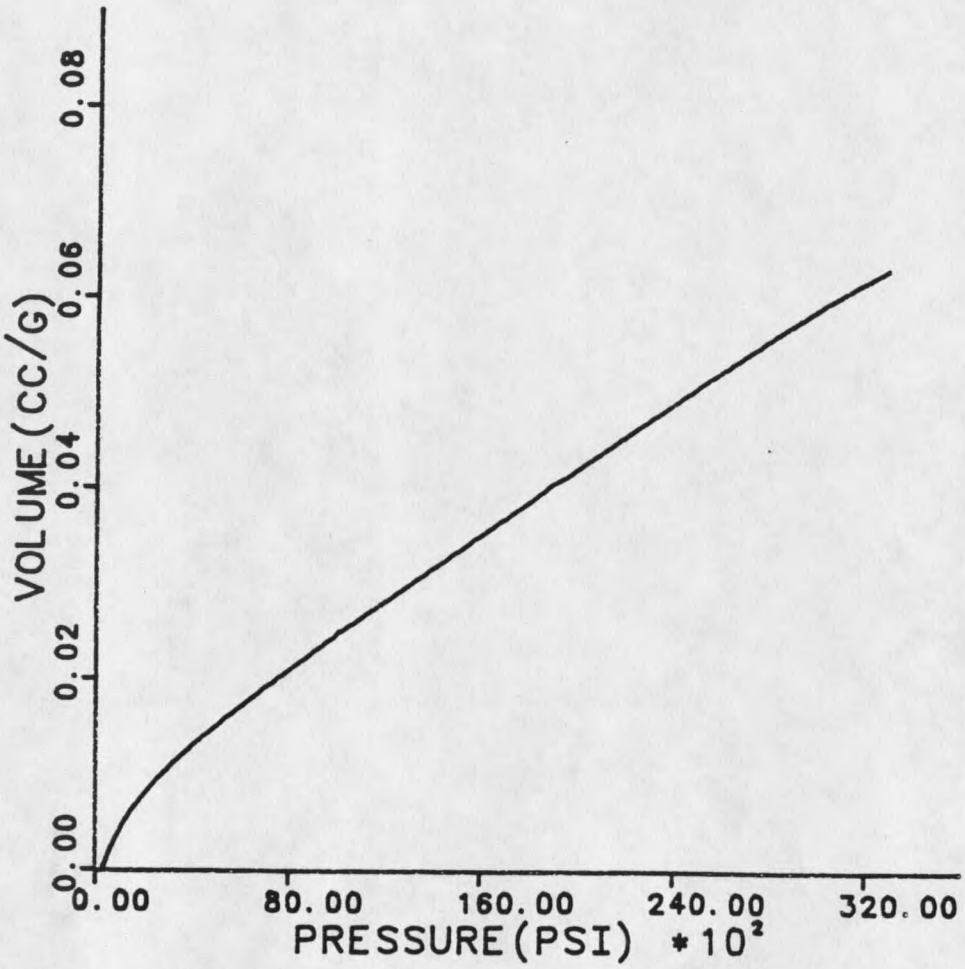

Figure 4. An example of raw mercury porosimetry data for coal sample E83-20.

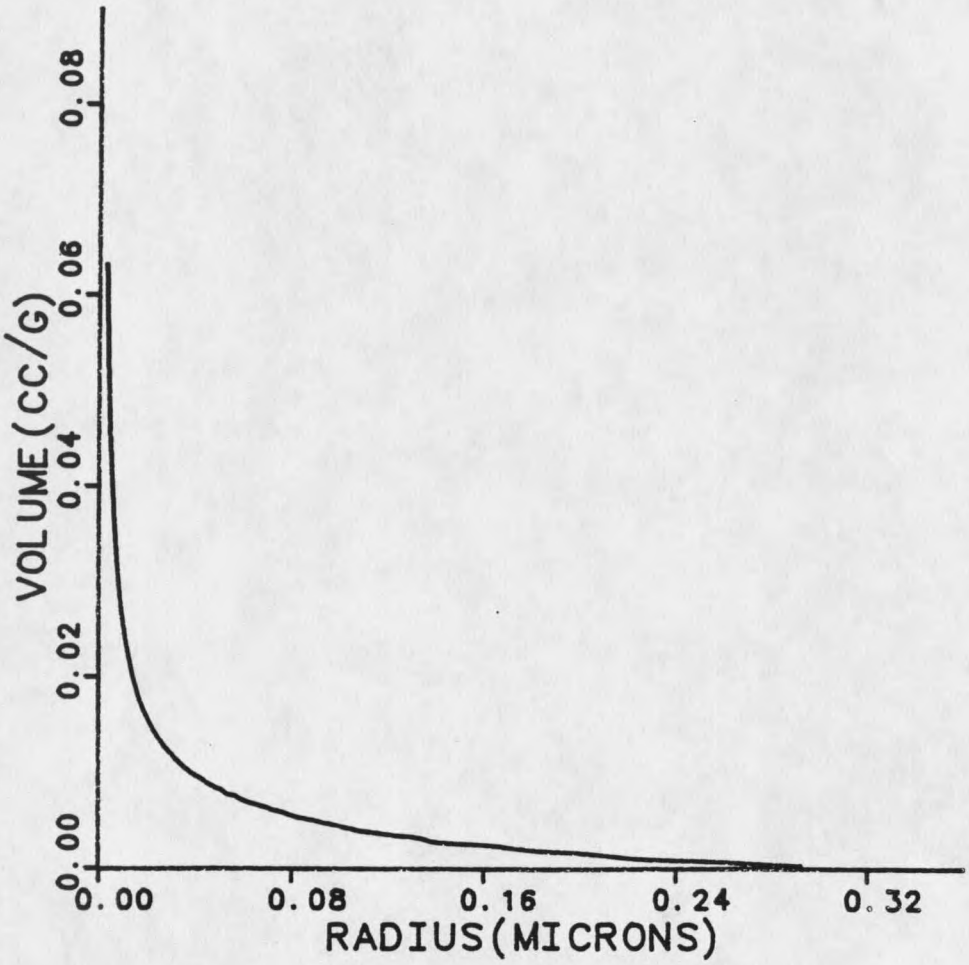

Figure 5. An example of radius versus volume data calculated from mercury porosimeter data for coal sample E83-20.

where n = number of pores

r = pore radius

l = pore length

According to the Washburn Equation, when pores are filled, the volumetric change with decreasing radius does not necessarily decrease since it corresponds to the filling of a new group of pores [19]. The corresponding change of volume when r decreases from r to r - dr is given by

$$dV = -D_V(r)dr \tag{6}$$

Where $D_V(r)$ is the volume pore-size distribution function. $D_V(r)$ is defined as the pore volume per unit interval of pore radius. Differentiation of Equation 2 assuming γ and θ are constant yields

$$Pdr + rdP = 0$$

which is then combined with Equation 6 to give

$$dV = D_V(r)r/PdP$$

rearranging,

$$D_V(r) = P/r(dV/dP) \tag{7}$$

This equation then gives the pore volume per unit radius interval. Figure 6 shows an example of the radius versus distribution for a given coal.

The last item calculated from the raw data is the surface area. It must be noted that the surface area calculated corresponds to only the surface area accessible to the mercury at ultimate pressure. In this study ultimate pressure was 33,000 psia which means that the surface areas reported correspond to that of pores with radius greater than 3.2 nm. The surface area is calculated from the same ideas that the Washburn Equation is based on. In the pore radius range dr there is a corresponding volume dV and surface area dS or

$$dS = PdV/\gamma|\cos\theta| \tag{8}$$

or

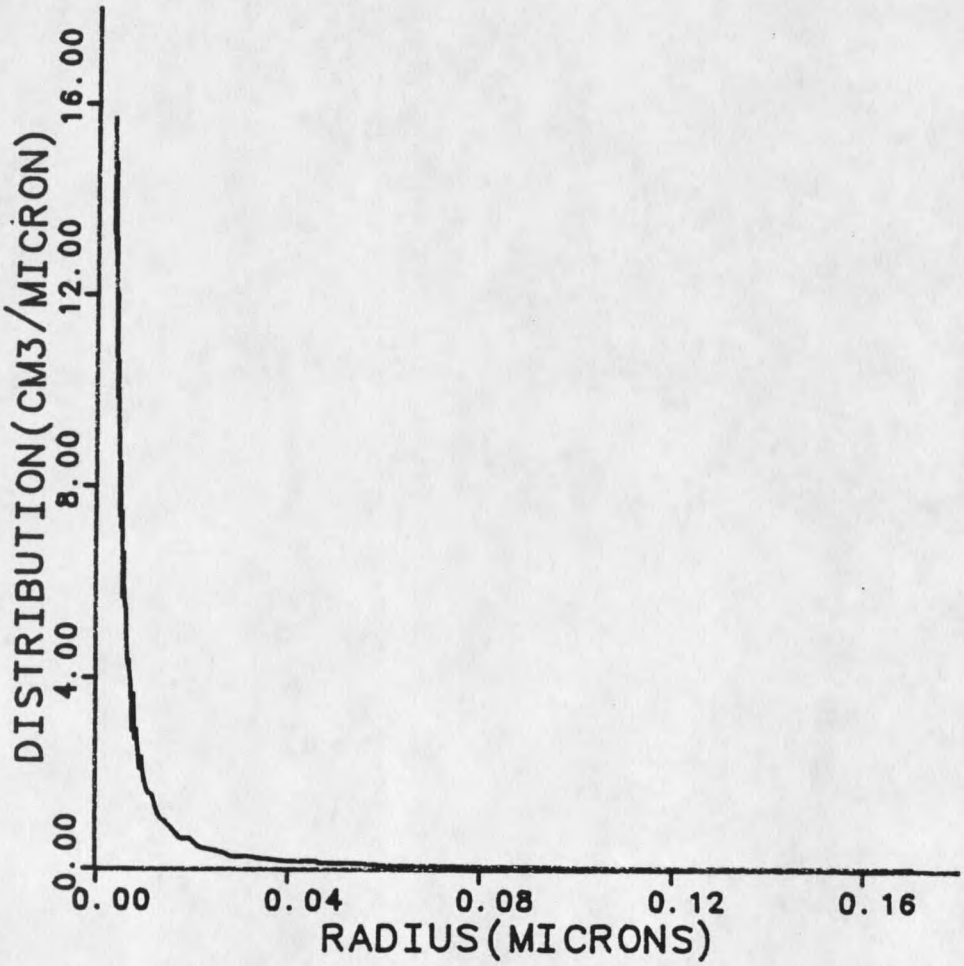

Figure 6. An example of the pore radius distribution for coal sample E83-20.

$$S = (1/\gamma|\cos\theta|)\int_0^V PdV \tag{9}$$

This method assumes no specific pore model. Using the values given previously for γ and θ Equation 9 reduces to

$$S = 0.0188\int_0^V PdV \tag{10}$$

where S will be in square meters, P is in psia, and V is in cubic centimeters. Graphical integration of the intrusion curve, pressure versus volume, is used to calculate the surface area. The area above the total curve to the maximum intruded volume is found. This number is normalized according to the scale of the graph to acquire a number with units of psia cm^3/g. This number equals $\int_0^V PdV$. This number is then inserted into Equation 10 to calculate the surface area.

Methane Adsorption

The basic equation used to calculate the quantity of methane adsorbed is the ideal gas law. (Actually, the Benedict-Webb-Rubin equation of state was used because of the high operating pressures but the ideal gas law will be used to explain the general procedure.)

$$PV = nRT$$

where P = Pressure

V = Volume

n = moles

R = Universal gas constant

T = Absolute temperature

From the adsorption apparatus, Figure 2, the pressure, temperature, and volume of tank 1 are known so the number of moles of methane being introduced into the sample chamber are known. Now the methane is passed into the sample chamber, tank 2, where the temperature, pressure, and void volume, the volume not occupied by the coal, are known. They are again used to calculate the number of moles. The second number of moles is subtracted

from the first, the difference is the number of moles adsorbed. This is then converted to volume and surface area. This procedure constitutes one data point. Tank 1 is refilled with methane which is then sent to tank 2 where more adsorption should occur and another point is generated at a higher pressure. Approximately five points between 300 and 2000 psia are measured for each coal sample analyzed. Table 1 shows an example of the raw data and the curve generated from this data is shown in Figure 7. The limits of certainty for these data are ± 0.14 atmospheres for the pressures and ± 1.0 degree for the temperatures.

The Benedict-Webb-Rubin Equation of State was chosen because of its applicability to light hydrocarbons [29]. Values of the constants were found for methane in the desired temperature and pressure range. Expressed in terms of the molar density ρ,

$$P = RT\rho + (B_oRT - A_o - C_o/T^2)\rho^2 + (bRT - a)\rho^3 + a\alpha\rho^6 + c\rho^3/T^2(1-\gamma\rho^2)\exp(-\gamma\rho^2) \quad (11)$$

Where P = Pressure

R = Universal Gas Constant

T = Absolute temperature

ρ = molar density

A_o = 1.855 $(l/gmol)^2$ atm

B_o = 4.26×10^{-2} (l/gmol)

C_o = 2.2257×10^4 $(l/gmol)^2 K^2$ atm

a = 4.94×10^{-2} $(l/gmol)^3$ atm

b = 3.38004×10^{-3} $(l/gmol)^2$

c = 2.545×10^3 $(l/gmol)^3 K^2$ atm

α = 1.24359×10^{-4} $(l/gmol)^3$

γ = 6.0×10^{-3} $(l/gmol)^2$

The values of the constants were taken from Cooper and Goldfrank [30].

Table 1. Raw Data Used to Determine the Volume of Methane Adsorbed for Coal Sample E83-20 Wet.

	Run #					
	1	2	3	4	5	6
Tank 1 Pressure (Atm)	2.97	3.18	3.12	3.24	3.65	4.33
Tank 1 Temperature (Kelvin)	297.0	297.5	299.0	298.0	298.0	299.0
Tank 2 Pressure (Atm)	23.52	46.92	67.94	89.09	112.09	141.48
Tank 2 Temperature (Kelvin)	297.0	299.0	298.0	298.0	298.0	300.0
Volume Adsorbed (Ft^3/ton)	205.8	488.5	707.2	871.1	1100.9	1193.9

Now that the volume of methane adsorbed at given pressures is known as the Dubinin-Polanyi method can be used to determine the surface area of the samples. A plot of $Log_{10}{}^2(P_O/P)$ versus $Log_{10}V$ is made and then extrapolated back to saturation, i.e. $(P_O/P) = 1$. As mentioned earlier, P_O is the vapor pressure of the adsorbate at the working conditions, P is the equilibrium pressure, and V is the volume of methane in cc/g. The value of $Log_{10}V$ is then used to calculate the surface area by Equation 12 below.

Surface Area =

$$10^{(LogV)}N\sigma/22.414(l/gmol)1000(cc/l)10^{18}(nm^2/m^2) \qquad (12)$$

Where N is Avogadro's Number and σ is the cross-sectional area of the adsorbate, in this case methane. The cross-sectional area that will be used is 0.181 nm^2 [31]. The pseudo vapor pressure of methane at the temperature of interest is not available so a saturation line on a reduced temperature-reduced pressure diagram was extended to determine it. The value was found to be 279 atm at a temperature of 23° C.

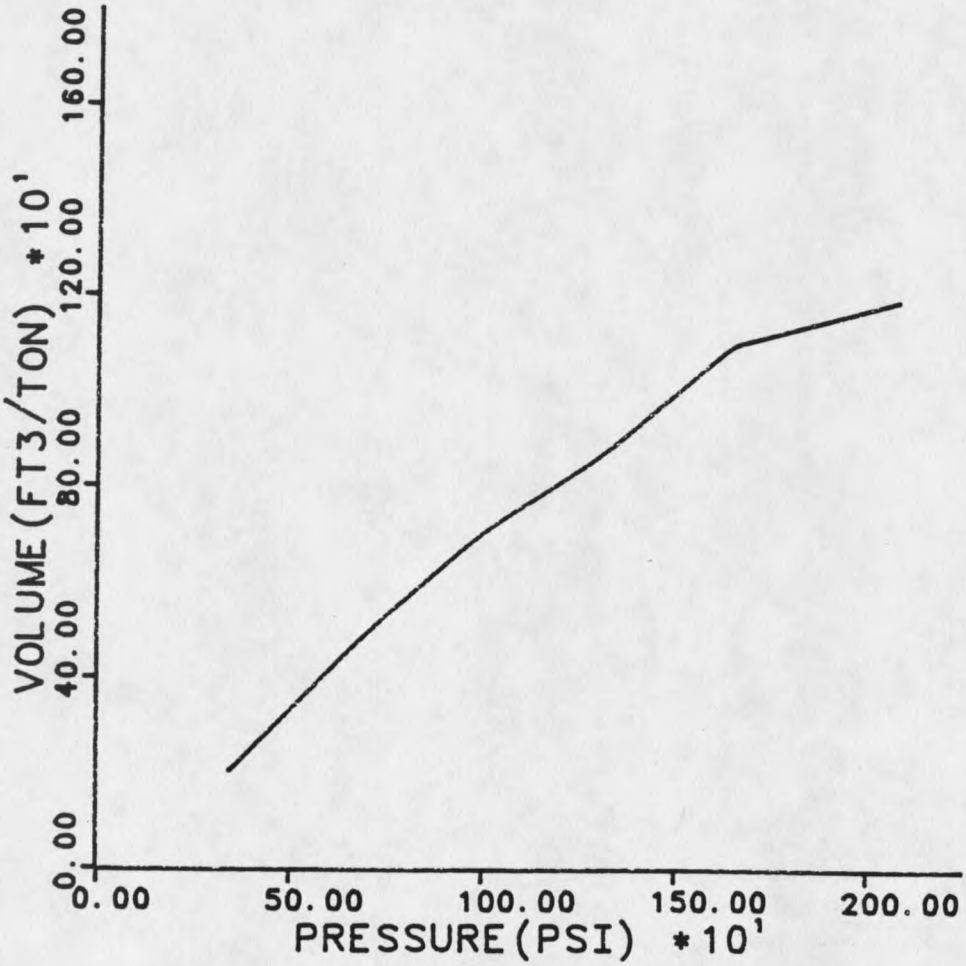

Figure 7. An example of methane adsorption data for coal sample E83-20 wet.

Carbon Dioxide Adsorption

The main result calculated from carbon dioxide adsorption is surface area. The raw data consists of either volume or weight adsorbed per gram of sample versus equilibrium pressure. This data is analyzed using the Dubinin-Polanyi relation. The value obtained at $(P_o/P) = 1$ is again used to calculate the surface area according to Equation 12. The vapor pressure used is 60.8 atm. Table 2 shows the raw data used to make the Dubinin-Polanyi plot, Figure 8. The final surface area calculated is also listed. The limit of certainty for these data are ± 0.01 mg for the weight of carbon dioxide adsorbed and ± 1.0 mm mercury for the pressures.

Table 2. Raw Carbon Dioxide Data Used to Create a Dubinin-Polanyi Plot for Coal Sample E83-20 MSU. The Surface Area Calculated From This Data is Also Listed.

	Run #		
	1	2	3
Weight of Methane (mg)	10.94	9.40	18.99
Log W_{CO_2}/W_{coal}	-2.542	-2.272	-1.986
Pressure (mm Hg)	52.0	110.0	244.0
$Log^2 (P_o/P)$	8.695	6.882	5.186
Surface Area = 233.6 m^2/g			

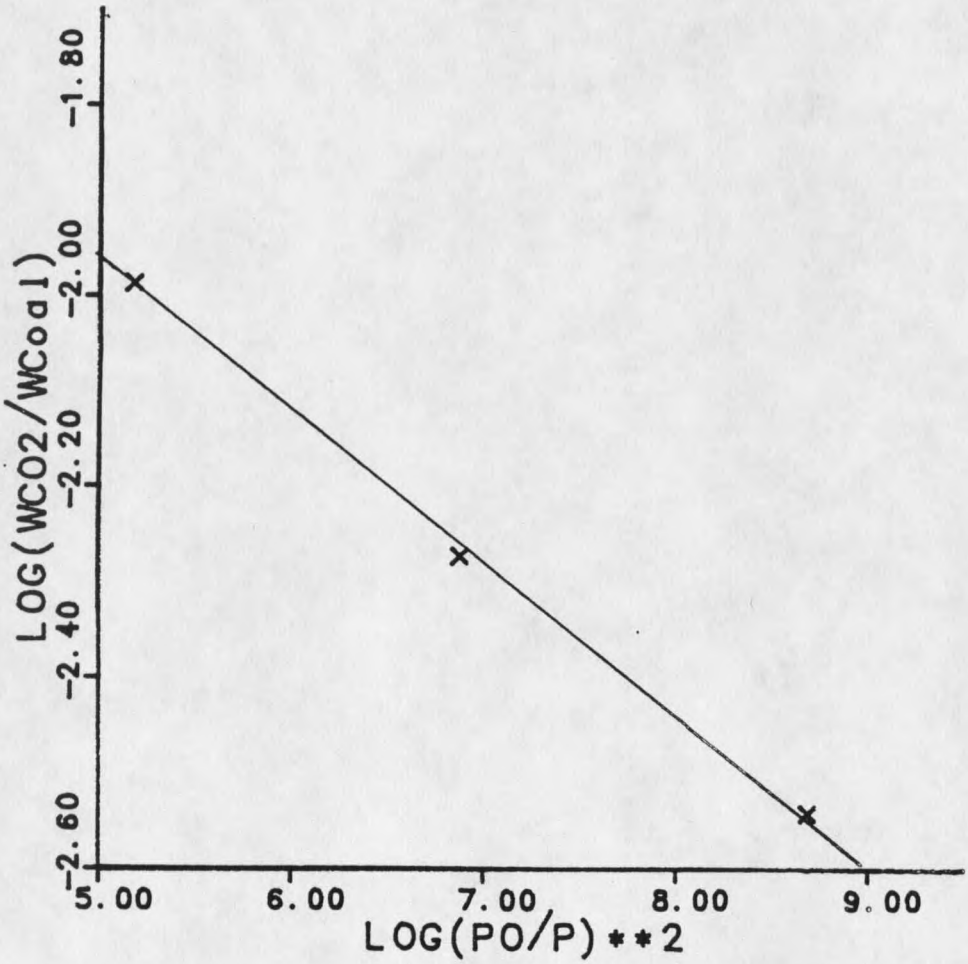

Figure 8. A Dubinin-Polanyi plot for calculating carbon dioxide surface areas for coal sample E83-20 wet.

RESULTS AND DISCUSSION

There are three important phenomena that were investigated in this research; adsorption of methane in coal, surface areas of coal calculated from carbon dioxide and methane adsorption, and mercury porosimetry analysis of coal.

Volume of Methane Adsorbed

The most important concept investigated was the quantity of methane that three Montana coals would hold under different pressures and at different moisture levels. Two moisture levels were investigated, wet coal and dry coal. The use of the term "wet coal" means that none of the moisture has been displaced except that which was lost between removing the coal from the ground and sealing it in a plastic bag. "Dry coal" has been dried at 110°C for 24 hours. It was found that each of the wet coals adsorbs approximately the same quantity of methane at pressures of 70 atmospheres and greater. At pressures of 100 atmospheres, which was the highest pressure investigated for all three wet coals, the quantity adsorbed ranged from 1100 to 1200 cubic feet per ton. It was also found, at pressures below 70 atmospheres, that each wet coal had a monotonic increase in methane adsorption with pressure.

The increase was different for each of the coals studied but the curves closely parallel each other. Figures 9, 10, and 11 show the curves of pressure versus volume of methane adsorbed for three wet coals. For coal sample E83-24 wet, Figure 10, one more data point would be desirable to indicate if the curve will continue upward or if it will level off as the other two tend to do. Unfortunately, the equipment would need to be rebuilt as the

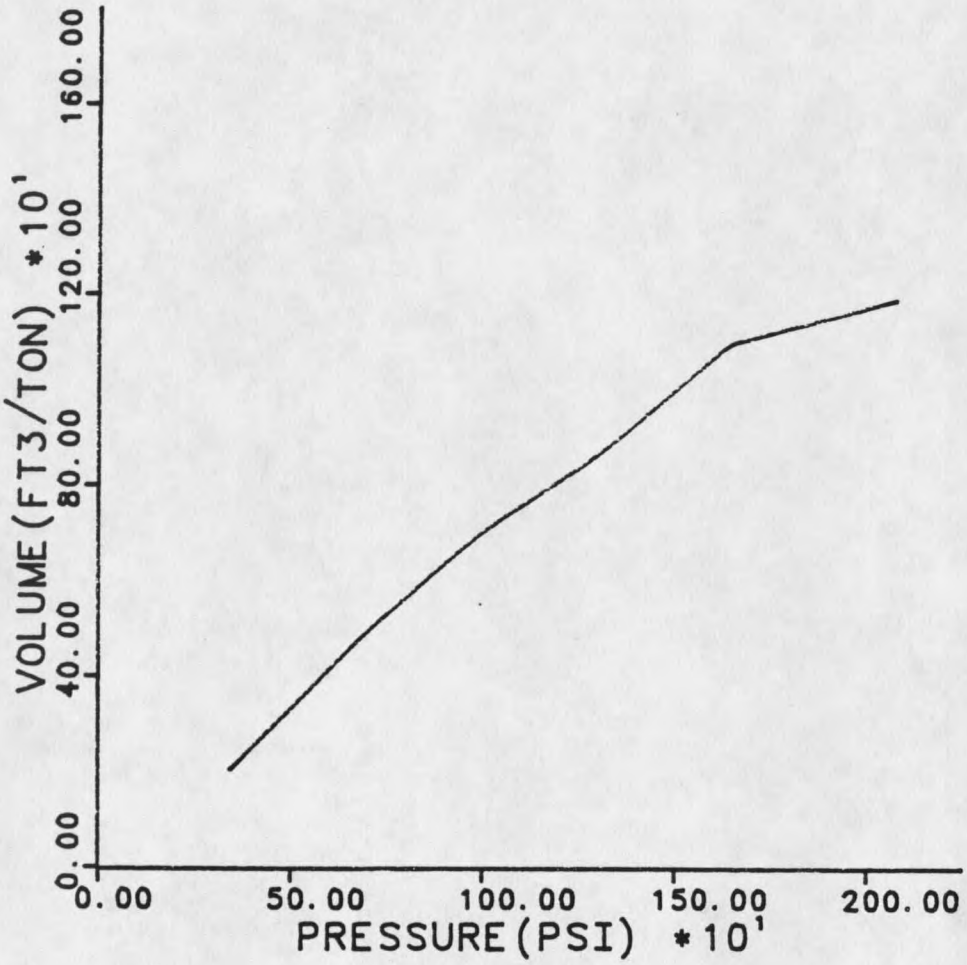

Figure 9. Pressure versus volume of methane adsorbed for coal sample E83-20 wet.

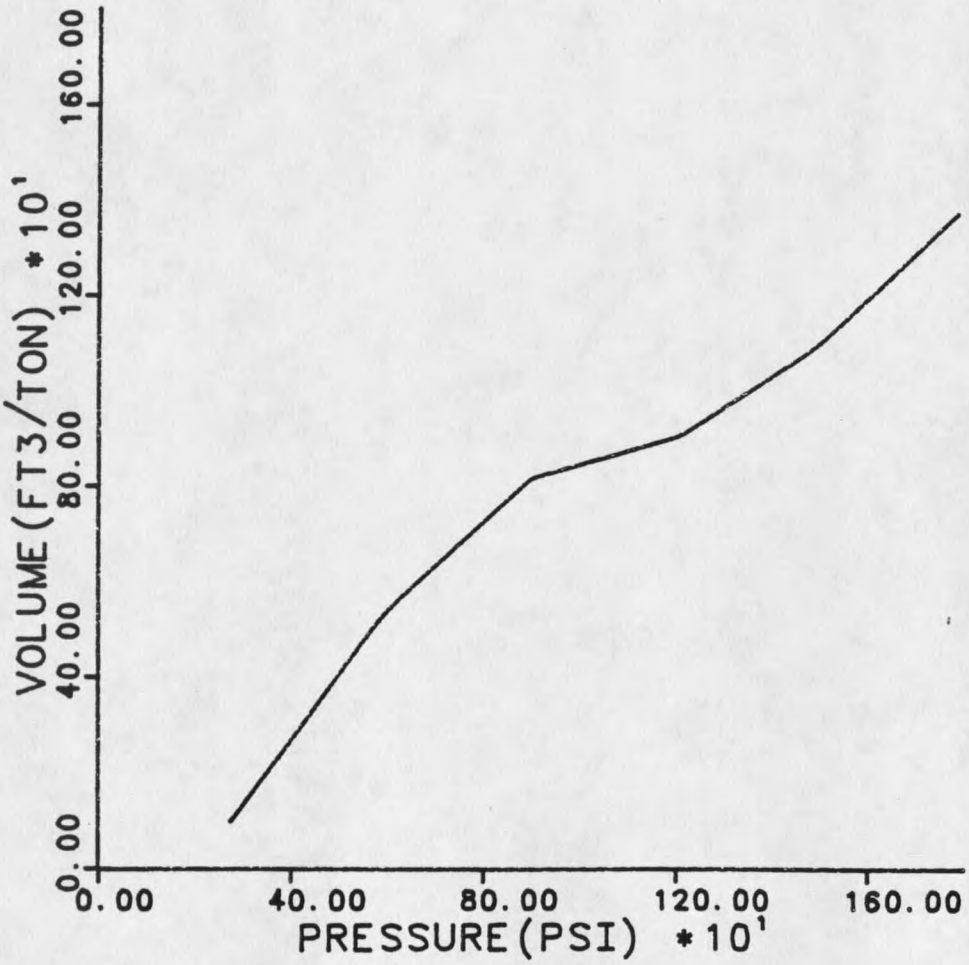

Figure 10. Pressure versus volume of methane adsorbed for coal sample E83-24 wet.

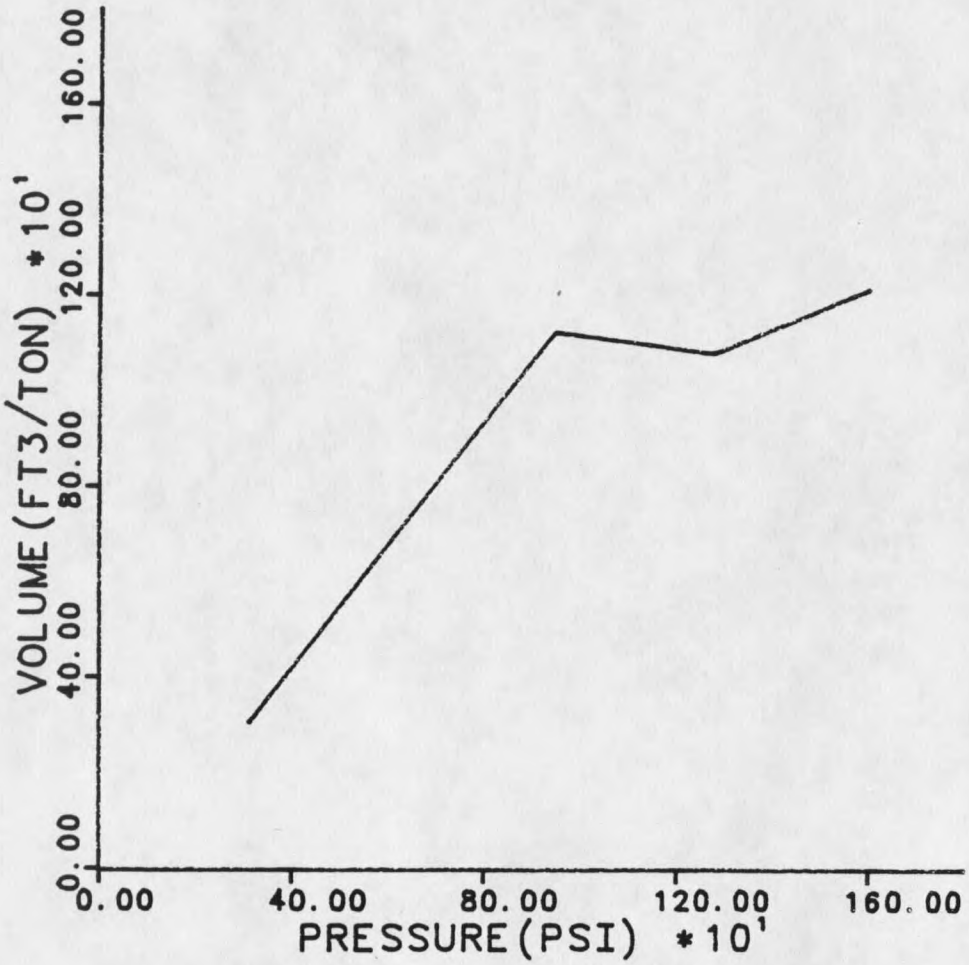

Figure 11. Pressure versus volume of methane adsorbed for coal sample E83-28 wet.

seal on the sample chamber will no longer hold the pressure that would be required to acquire the additional point.

Figures 12, 13, and 14 are the pressure versus volume curves for each of the three coals discussed above after drying. Due to the sporadic nature of the data for coal E83-24 this data will basically be disregarded in the following discussion. It is believed that upon drying E83-24 undergoes significant alteration causing inaccurate data. Examination of the other two coals indicates adsorption patterns similar to those exhibited by the wet coals. The two dry coals however, adsorb approximately the same quantities of methane at 20 to 70 atmospheres pressure. Also, at pressures of 70 atmospheres and higher the quantities adsorbed slightly diverge from one another.

Dry coals adsorb two to three times the amount adsorbed by wet coals in the same pressure range. Values found are 4330 ft^3/ton at 131 atmospheres for E83-20 dry and 3770 ft^3/ton at 128 atmospheres for E83-28 dry. It is believed that the relationship between the amounts adsorbed for wet and dry coals is a function of moisture lost upon drying and site characteristics. Airey [25] mentions that the model used to derive Equation 3 assumes the amount of methane desorbed (i.e., the initial amount of methane present in the coal) is affected by the amount of moisture present. But, his coals only vary from 5 to 6.2 percent moisture. He also states that the effect of different amounts of moisture is masked by the large variation of particle sizes studied. He does not report any results from using the same size samples while varying the moisture content. Losinski [32] indicates that as coals are dried some carbon dioxide, along with the water, is removed causing different sites to be available as well as increasing the number of adsorption sites. Further study in this area is needed to determine this relationship.

Table 3 lists some of the properties of the coal being analyzed. The ultimate analysis listed was done on dry coal only, because the Carlo Erba apparatus used is greatly affected by any excess moisture. The time required for the methane apparatus to reach equilibrium

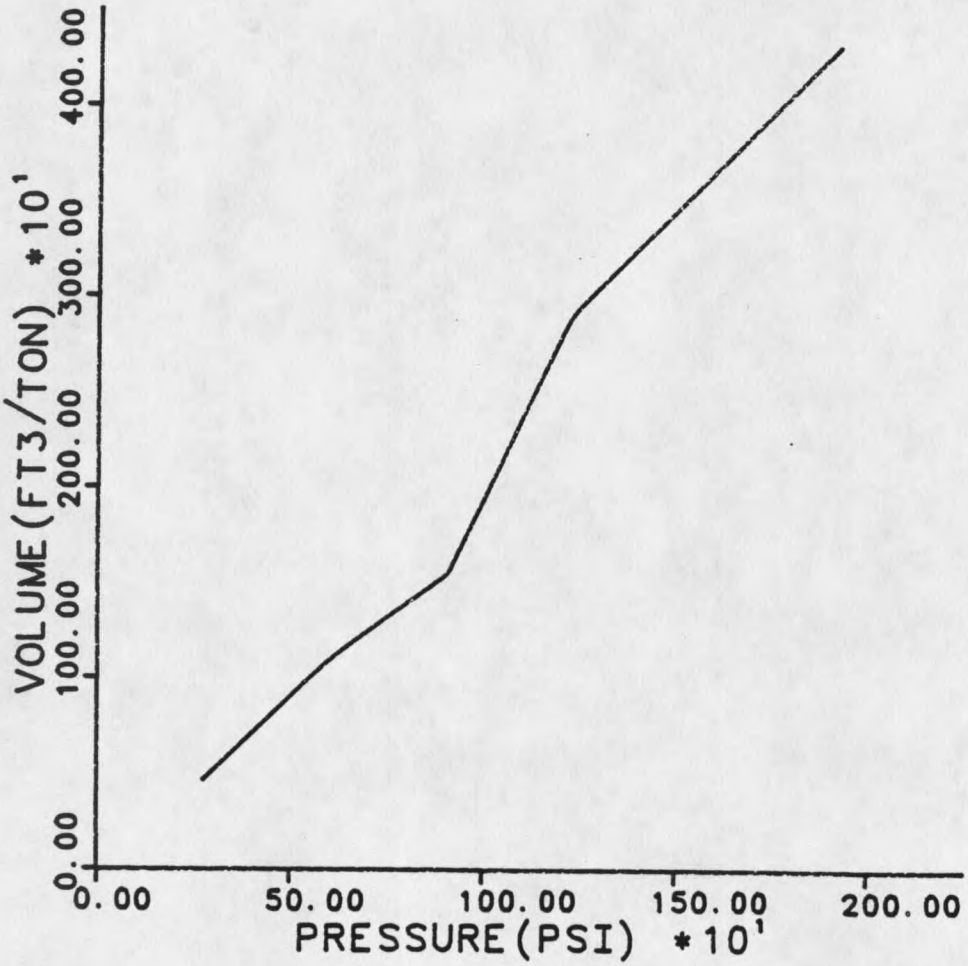

Figure 12. Pressure versus volume of methane adsorbed for coal sample E83-20 dry.

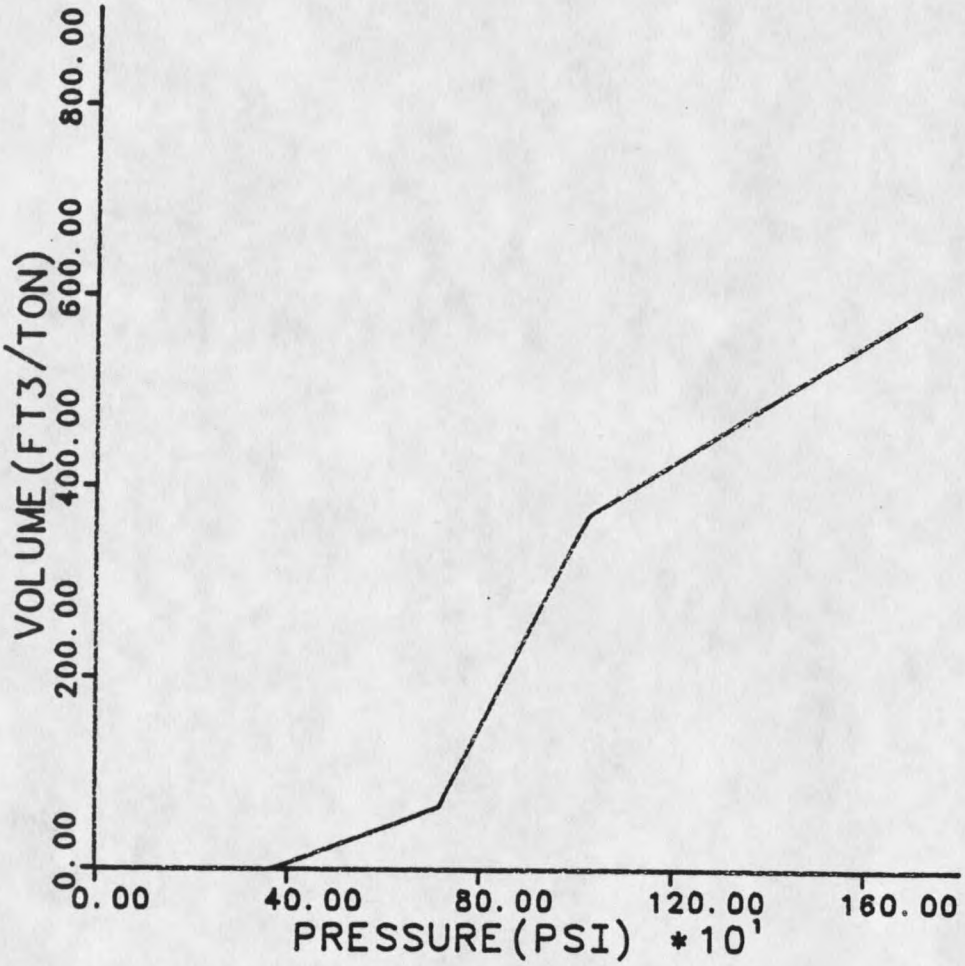

Figure 13. Pressure versus volume of methane adsorbed for coal sample E83-24 dry.

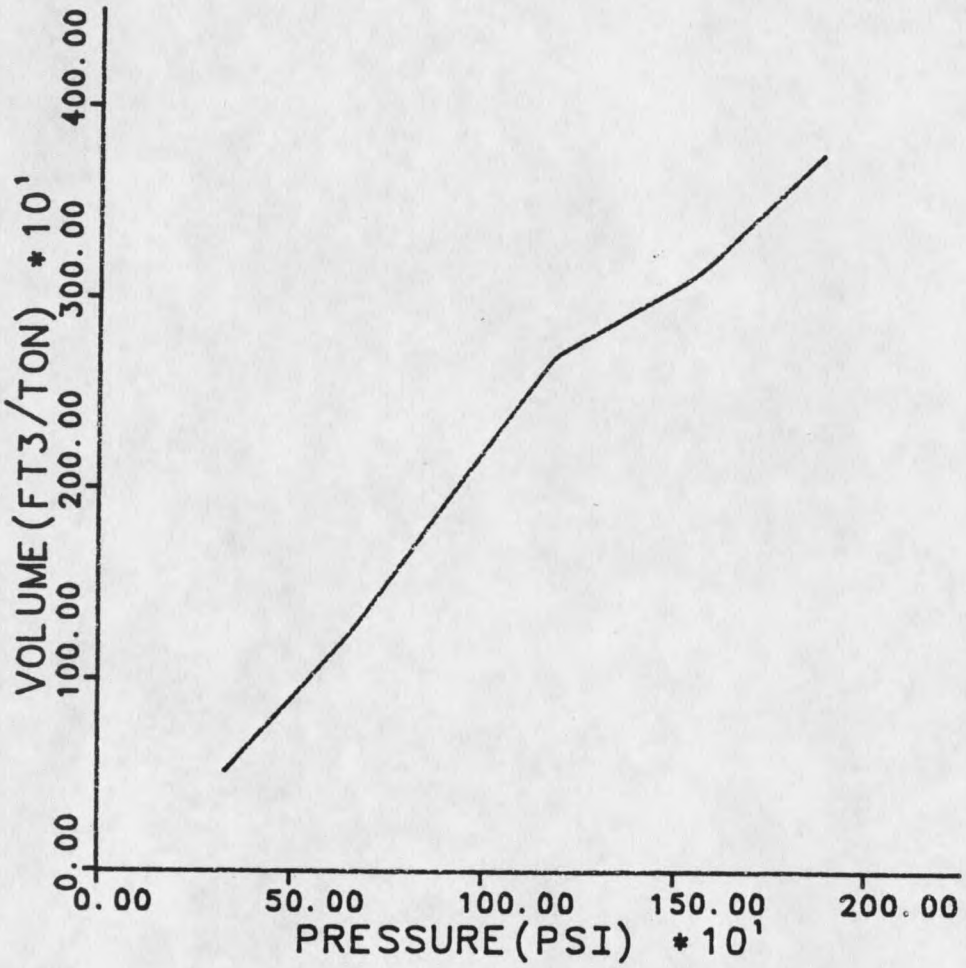

Figure 14. Pressure versus volume of methane adsorbed for coal sample E83-28 dry.

Table 3. Physical Characteristics of Coal Samples E83-20, E83-24, and E83-28. Duplicate runs are given.

Coal Sample	Weight Percent Moisture ± 0.01	Density (g/cm³) ± 0.01 Dry	Wet
E83-20	7.76	1.29	1.24
E83-20	6.93	1.25	1.27
E83-24	15.31	1.34	1.33
E83-24	15.18	1.31	1.32
E83-28	9.42	1.27	1.31
E83-28	9.45	1.31	1.35

Ultimate Analysis of Dry Coal — Carlo Erba

Coal Sample	Nitrogen	Carbon	Hydrogen
E83-20	1.22	71.33	4.78
E83-20	0.97	69.91	4.43
E83-24	1.15	65.79	4.18
E83-24	1.24	66.85	4.37
E83-28	1.14	66.12	4.52
E83-28	1.32	64.89	4.63

Coal Sample	Seam Depth (ft)	% Ash (Wet Basis) ± 0.01
E83-20	406-433	1.77
E83-20		2.01
E83-24	95-121.5	3.04
E83-24		3.65
E83-28	175-190	6.35
E83-28		1.93
E83-28		13.73

was originally assumed to be 8 hours. Upon closer examination it was found that 15 hours is needed. Because of the method used to increase the pressure in the sample chamber a negative change is feasible. The explanation for this is that some desorption probably occurred when the sample chamber pressure was boosted. This meant that extra time was needed to reach the new equilibrium point; also, the boosting procedure, which used liquid nitrogen, caused increased equilibrium time to allow the system to get back to room temperature. The slight dip on Figure 11 is probably explained by this. Some of the points on the methane pressure versus volume curves that obviously did not reach equilibrium

were discarded. The raw data and corresponding curves are presented in the Appendices. The accuracy of the data reported is estimated to be with ± 3.7 percent.

Surface Areas Calculated From Methane and Carbon Dioxide Adsorption

As stated earlier the Dubinin-Polanyi (D-P) Method was used to calculate the surface areas of the coals being studied. Both carbon dioxide and methane were used as adsorbates. Example carbon dioxide and methane D-P plots are shown in Figures 15 and 16, the rest are in the Appendices. Most of the plots exhibit reasonable straight lines allowing for good accuracy in calculating the intercept at $P_0/P = 1$. The least squares method was used to fit the data. The intercept is then used to calculate the surface area. Table 4 lists the surface area values calculated. Three surface areas values are calculated from methane adsorption. These correspond to including higher and higher pressures in the calculation. This demonstrates how the areas change, usually getting closer to the carbon dioxide value. The cross-sectional areas used for carbon dioxide and methane molecules were given previously.

Table 4. Surface Areas Calculated From Methane and Carbon Dioxide Adsorption. Square meters per gram ± 0.2.

Adsorbate Pressure Range	Methane 0 to 1000 psia	Methane 0 to 1300 psia	Methane 0 to 1600 psia	Carbon Dioxide 0 to 5.8 psia
E83-20 wet	193.1	194.3	205.6	
E83-20 dry	406.5	541.3	595.6	233.6
E83-28 wet	308.7	262.4	247.5	
E83-28 dry	615.9	659.0	656.3	229.8
E83-24 wet	369.2	293.4	271.9	
E83-24 dry	—	164.0	97.0	173.1

Examination of Table 4 indicates that low pressure carbon dioxide analysis can be used to predict high pressure methane results for wet coals, high pressure being 1000 psia and greater. Smith and Williams [13] report similar results. Again, coal samples E83-24 gives unusual results as compared to other coals. The decrease in surface area exhibited by

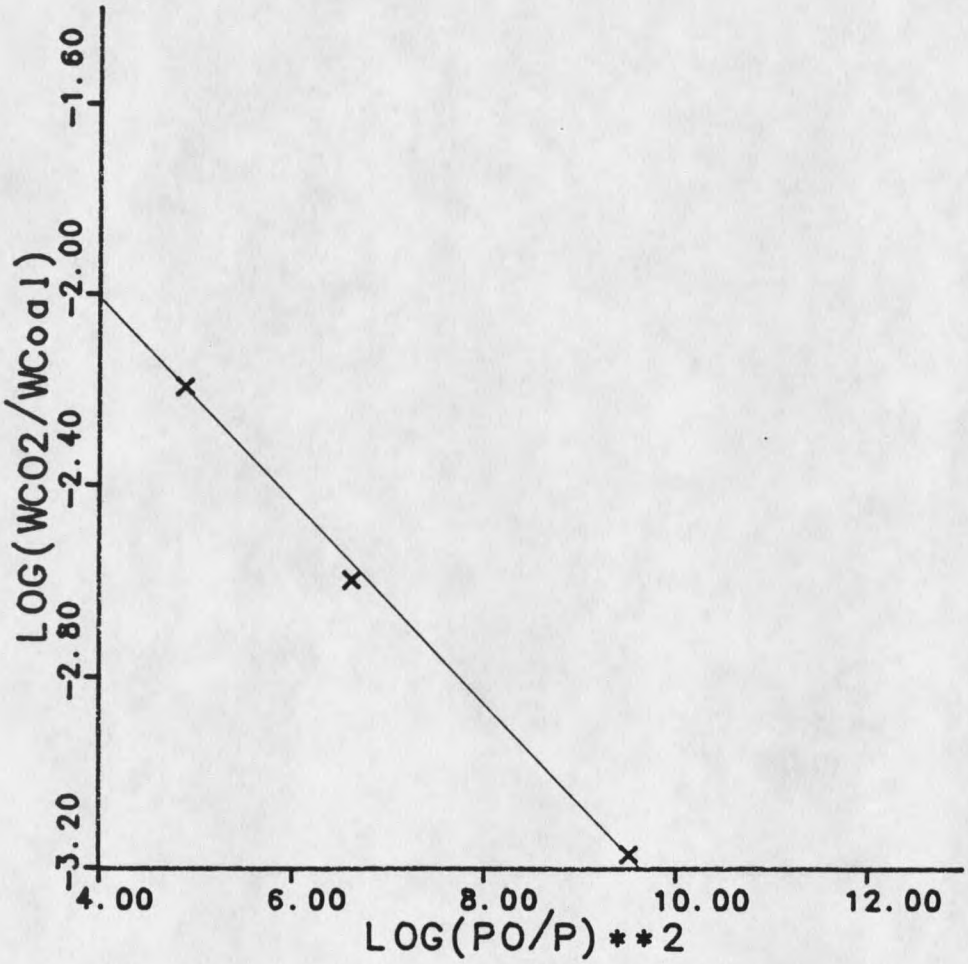

Figure 15. Dubinin-Polanyi plot, $Log^2 (P_o/P)$ versus Log V, for carbon dioxide adsorption on coal sample E83-28.

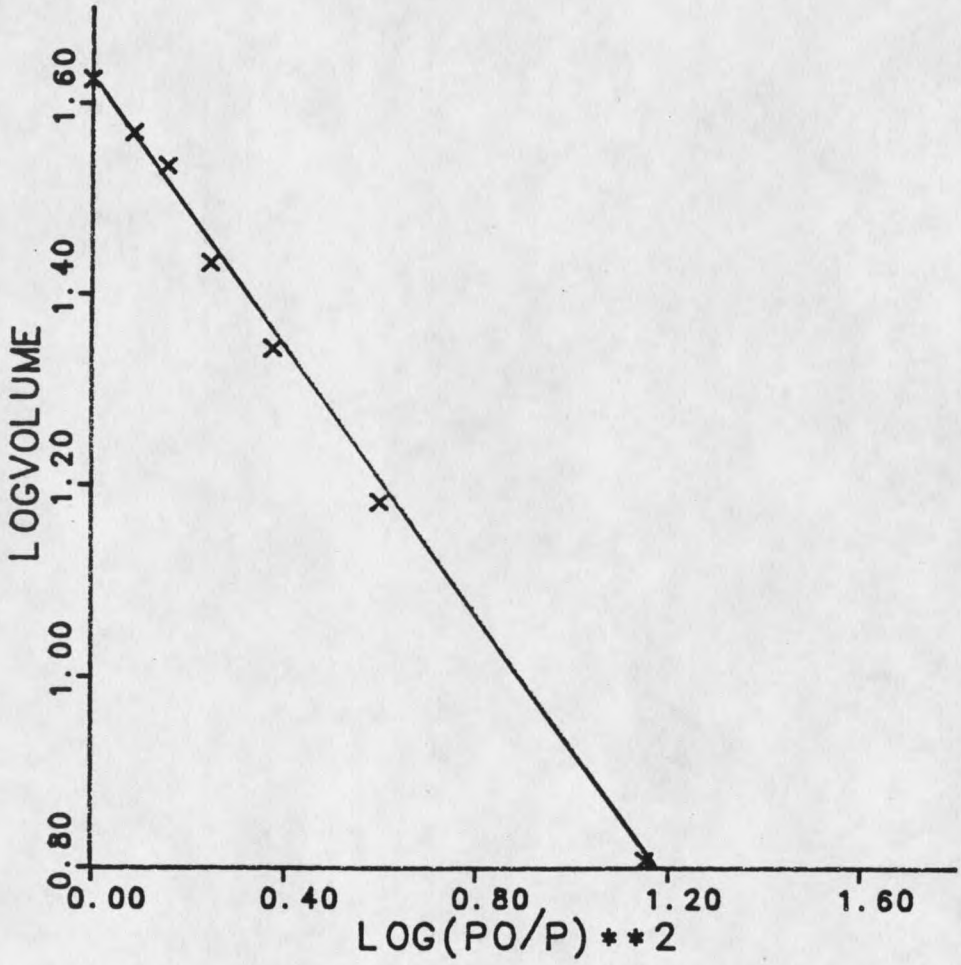

Figure 16. Dubinin-Polanyi plot for methane adsorption on coal sample E83-20 wet.

E83-28 wet as pressure of methane increases is possibly explainable by examining the D-P plot. Figure 17 indicates that the lowest pressure point is probably given too much emphasis when determining the intercept. If that point is disregarded, a surface area of 229.9 square meters per gram is calculated. This number is on the order of that obtained by the carbon dioxide adsorption. The decrease in surface areas may also have something to do with the increasing amount of methane in the water-methane ratio. The competition for sites is continually changing which may cause different amounts of each species to be adsorbed. Further examination of Table 4 indicates that the methane surface areas determined for dry coals are almost three times the carbon dioxide and wet coal methane surface areas. A possible explanation is that condensation may be occurring in the smallest pores at high pressures. These pores are probably not available in wet coals because they are occupied by water. The range of operating pressures being used for methane adsorption is actually too high to allow the Dubinin-Polanyi relationship to be strictly valid. See the discussion in the Surface Area section of the Literature Search. The D-P relationship is very good for the carbon dioxide data reported. Again, it is believed that the relationship between the wet and dry methane surface areas is a function of the moisture lost upon drying and site alteration.

Mercury Porosimetry Analysis of Coal

Mercury porosimetry has proven to be of little use when studying the quantity of methane adsorbed in coal because of its microporous structure. Mercury porosimetry however, can be used to help determine if degassing a coal bed is feasible. This is true because mercury penetration indicates if a bed has a significant number of macropores. Macropores are necessary along with fracturing so that the gas has easy access to the exterior. The volume of pores intruded by mercury was 0.0633, 0.0108, and 0.0037 cubic centimeters per gram for coal sample E83-20, E83-24, and E83-28, respectively. These

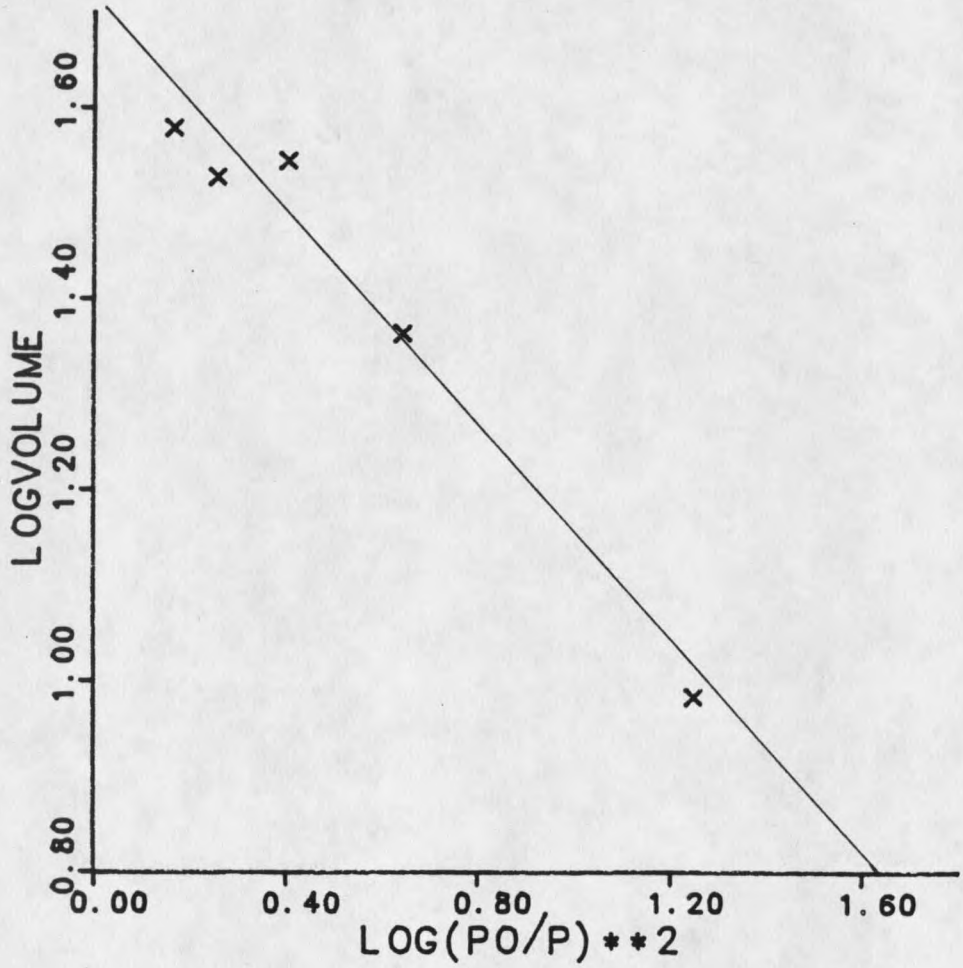

Figure 17. Dubinin-Polanyi plot for methane adsorption on coal sample E83-28 wet.

volumes correspond to pores with radius greater than 3.23 nm, which corresponds to an ultimate mercury pressure of 33000 psia. The surface areas calculated from these data are 17.92, 1.74, and 1.08 square meters per gram for E83-20, E83-24, and E83-28, respectively. These data indicates that coal E83-20 would be the easiest to degas. Comparison of the surface area values calculated from mercury intrusion to those given in Table 4 indicate that the mercury is intruding into only the largest pores. Another good indication that the mercury only intrudes into the macropores is provided by the radius versus pore-size distribution curves. Figures 18, 19, and 20 show that the greatest number of pores are in the lowest radius range measurable but no peaks are evident. Examination of helium intrusion would give a much more complete picture.

Estimates of Methane Available in Montana Coals

Estimates of the quantity of methane available have been made for the coals studied. An approximate value of the pressure exerted on the coal in-situ was done by using the relationship, 3 kilometers depth equals 1 kilobar of pressure [33]. This was linearly extrapolated to the seam depth and that number was used to estimate the quantity of methane present. These pressures will represent the maximum pressures that can be present. This is because near the surface the maximum pressure possible is the lithostatic pressure, no overpressure pockets are possible because fluids have avenues of escape available. Table 5 lists the depths, pressures and quantities of methane calculated. It also lists the depths of the other coal seams found in each of the cores used to acquire the coals studied [34]. The methane quantities are estimated for each of the seams by assuming similar properties to the coal sample studied from each core. The values reported are the maximum methane quantities available from the pores but none of the natural fractures have been included. It should be noted that the shallow beds are probably not at maximum pressure. An overall average value is calculated so that a rough estimate of the entire Montana reserve can be

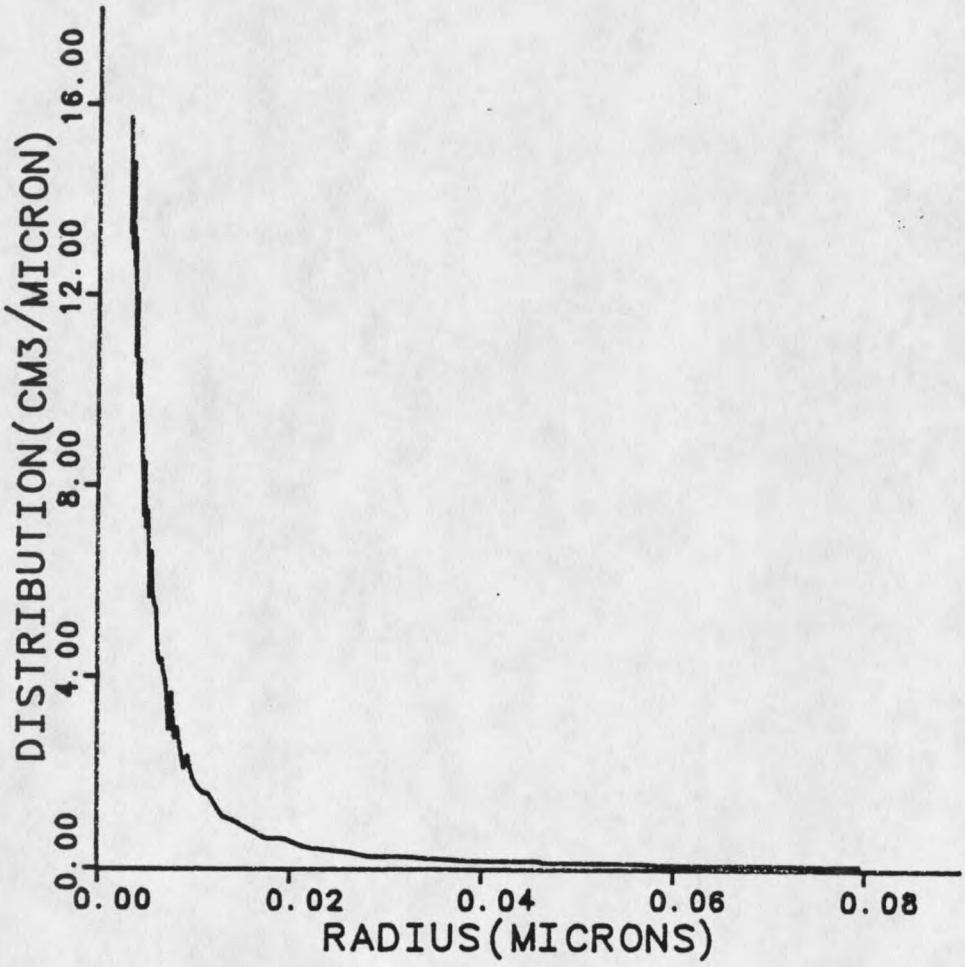

Figure 18. Radius distribution indicated by mercury intrusion of coal sample E83-20.

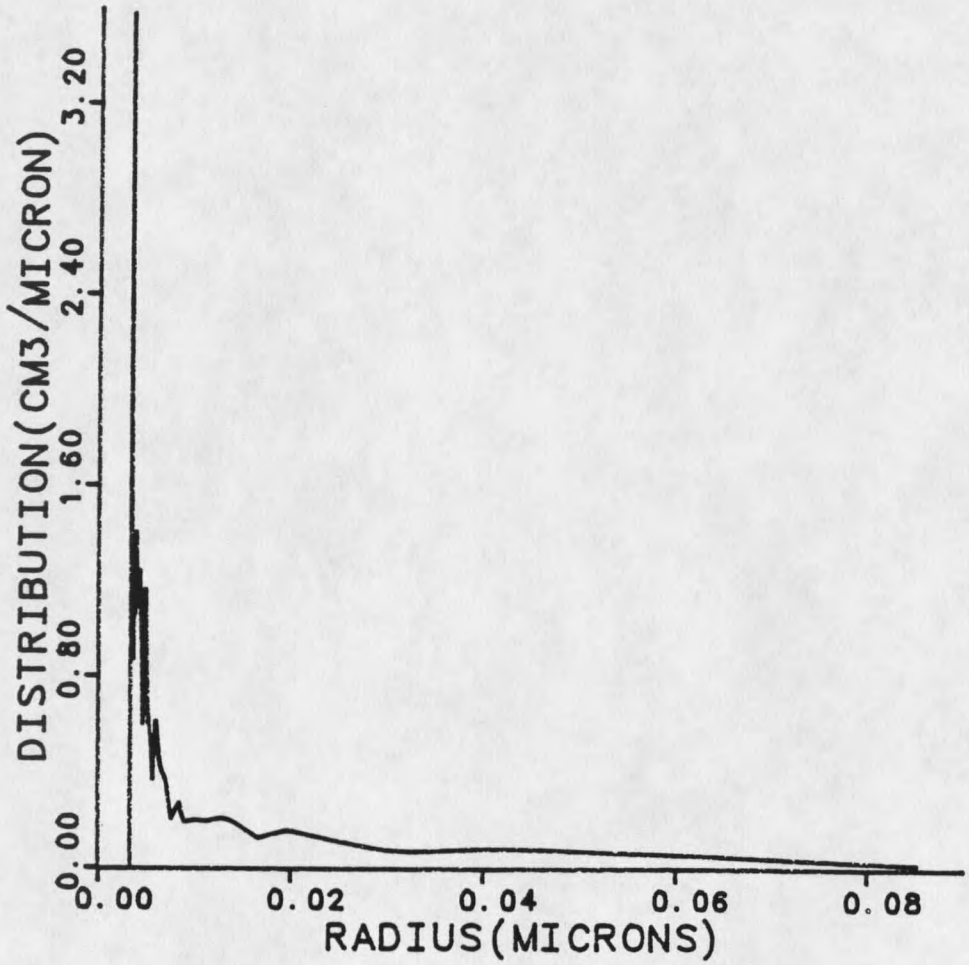

Figure 19. Radius distribution indicated by mercury intrusion of coal sample E83-24.

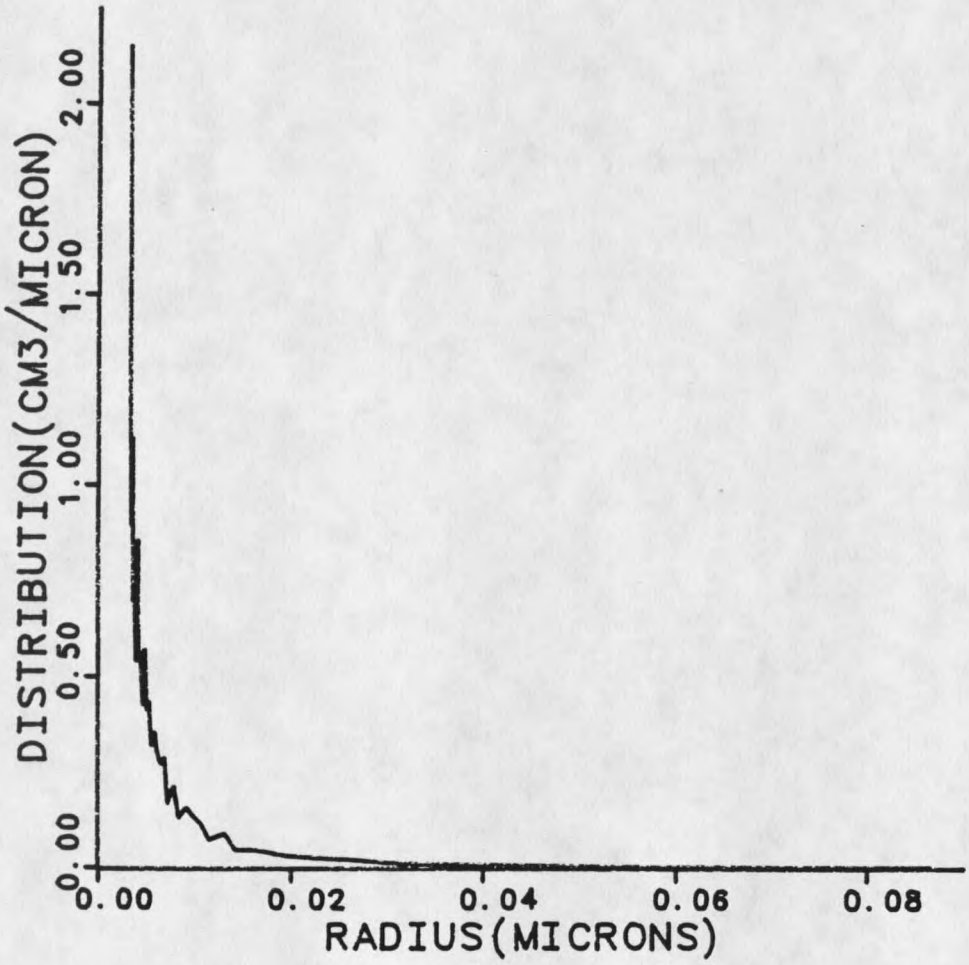

Figure 20. Radius distribution indicated by mercury intrusion of coal sample E83-28.

Table 5. Depths, Pressures, and Estimates of Methane Available for the Coal Samples Investigated.

Samples Studied	Seam Depth (ft) ± 1.0	Pressure (atm) ± 0.2	Methane Available (ft^3/ton) ± 0.2
E83-20	419.5	42.0	430.3
E83-28	182.5	18.3	251.0
E83-24	108.25	10.8	40.0

Coal seams from the same core samples as those studied above.

Sample	Seam Depth (ft) ± 5.0	Pressure (atm) ± 0.2	Methane Available (ft^3/ton) ± 0.2
E83-20	180	18.0	139.4
	240	24.1	213.0
	295	29.6	279.5
	420	42.1	430.5
	495	49.6	516.6
	570	57.1	594.7
	665	66.7	694.7
	732	73.4	749.7
	770	77.2	767.2
	870	87.2	856.3
	970	97.3	953.0
	985	98.8	968.0
E83-24	108	10.8	40.0
	250	25.1	227.8
	295	29.6	318.9
	365	36.6	460.7
	395	39.6	521.4
E83-28	182	18.2	251.0
	275	27.6	429.0
	425	42.6	716.1
	580	58.1	1013.8
	600	60.2	1054.1
	625	62.7	1102.1

made. The value calculated is 12.8×10^{13} cubic feet at standard conditions. Overall this is probably a fairly accurate estimate because a result with some lignite coal, at higher pressures than is expected, is included in the average, while there is no result with bituminous

coal included. It is expected that bituminous coal will contain more methane than subbituminous or lignite. It is suggested that deep bituminous and subbituminous coals be investigated to locate the best possible methane sources.

CONCLUSIONS

1. The wet coals investigated tend towards similar quantities of methane adsorbed. This should not be necessarily taken as a general truth for all Montana coals. Any coal of interest should be examined to determine the individual properties of that coal.
2. Examination of quantities of methane attainable on dried coals give good data for study but should not be used to project in-situ methane available.
3. Low pressure carbon dioxide adsorption can be used to estimate expected high pressure methane adsorption.
4. The relationship between wet and dry methane surface areas is approximately 1:3. Further study is needed to better quantify the relationship of moisture content and site alteration upon drying to methane adsorption.
5. Mercury porosimetry is of little value to determine methane adsorption when used on coal because of its highly microporous structure.
6. The estimated methane content of the total Montana coal reserve is 12.8×10^{13} cubic feet at standard conditions.

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REFERENCES

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APPENDICES

APPENDIX A

DUBININ-POLANYI CURVES USED TO CALCULATE SURFACE AREAS

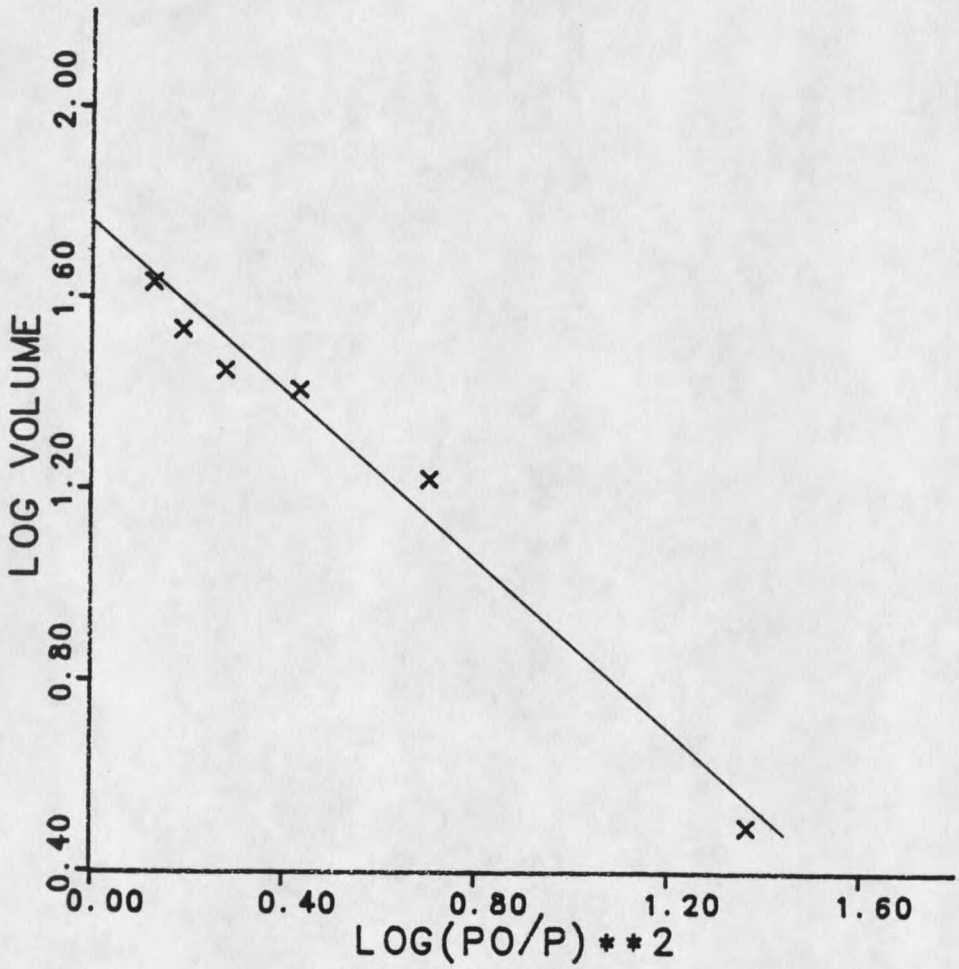

Figure 21. Dubinin-Polanyi plot for methane adsorption on coal sample E83-28 wet.

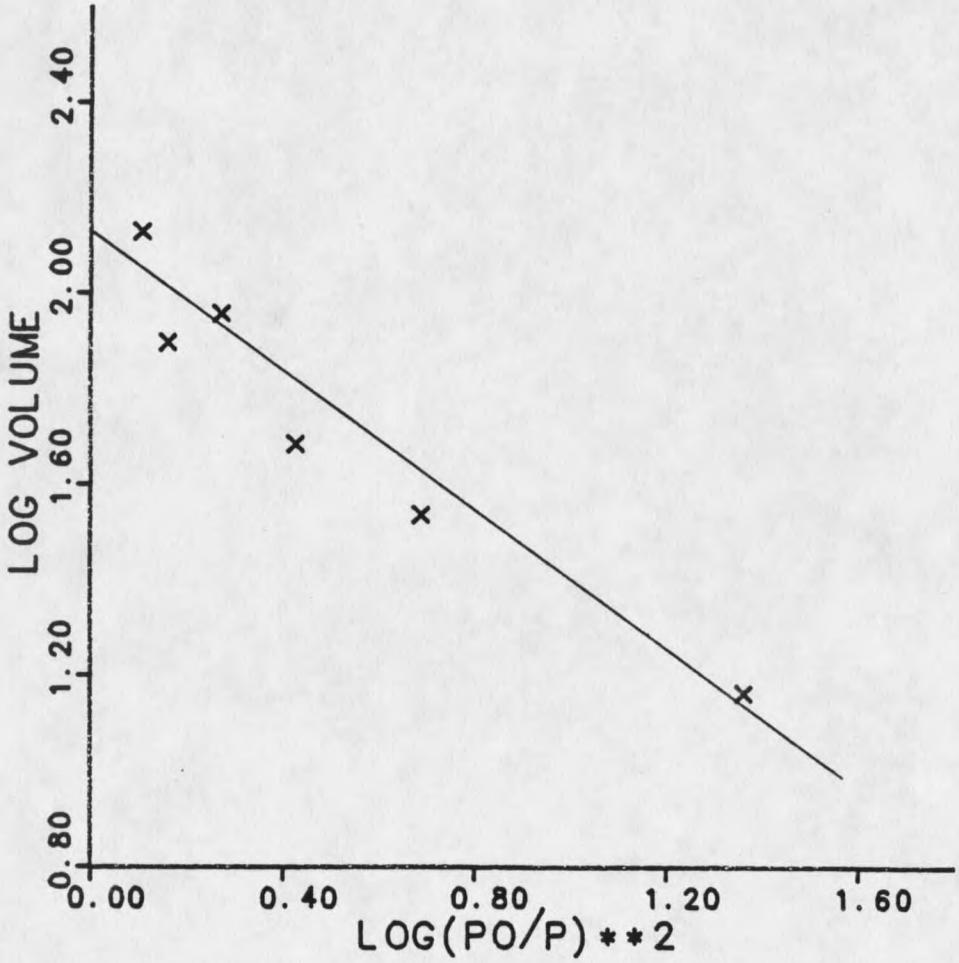

Figure 22. Dubinin-Polanyi plot for methane adsorption on coal sample E83-20 dry.

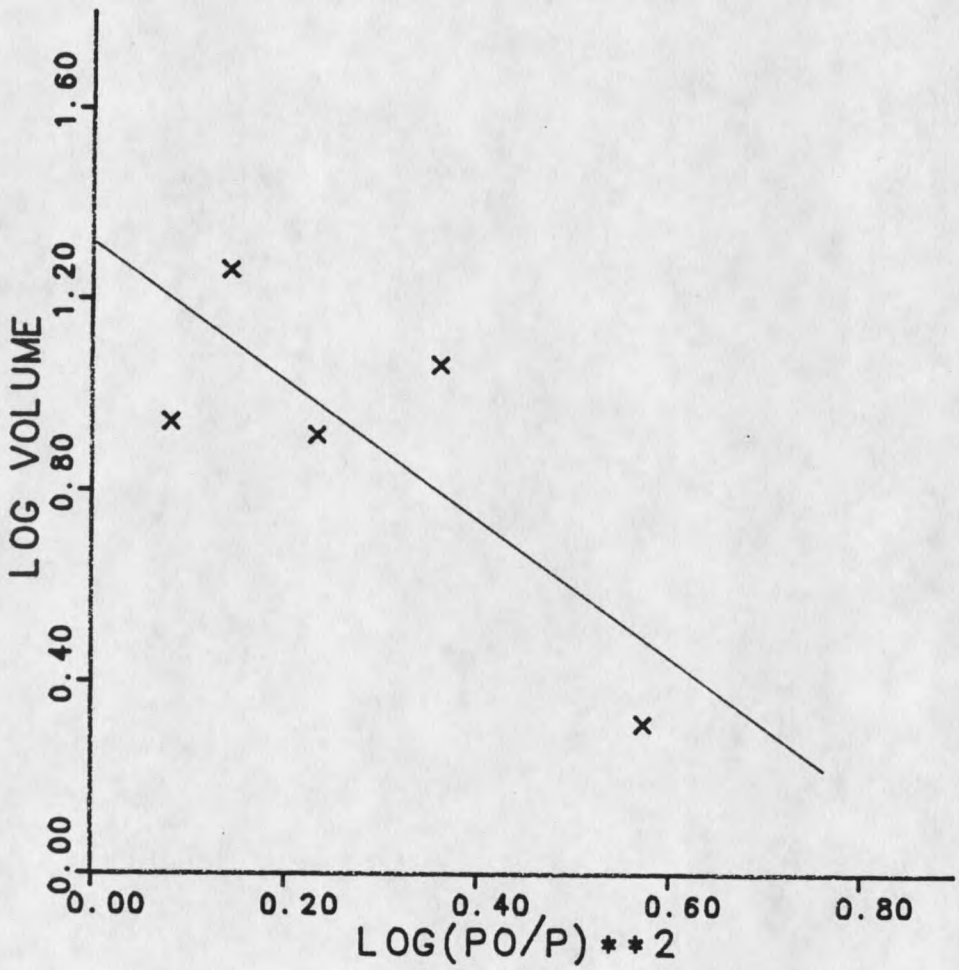

Figure 23. Dubinin-Polanyi plot for methane adsorption on coal sample E83-24 dry.

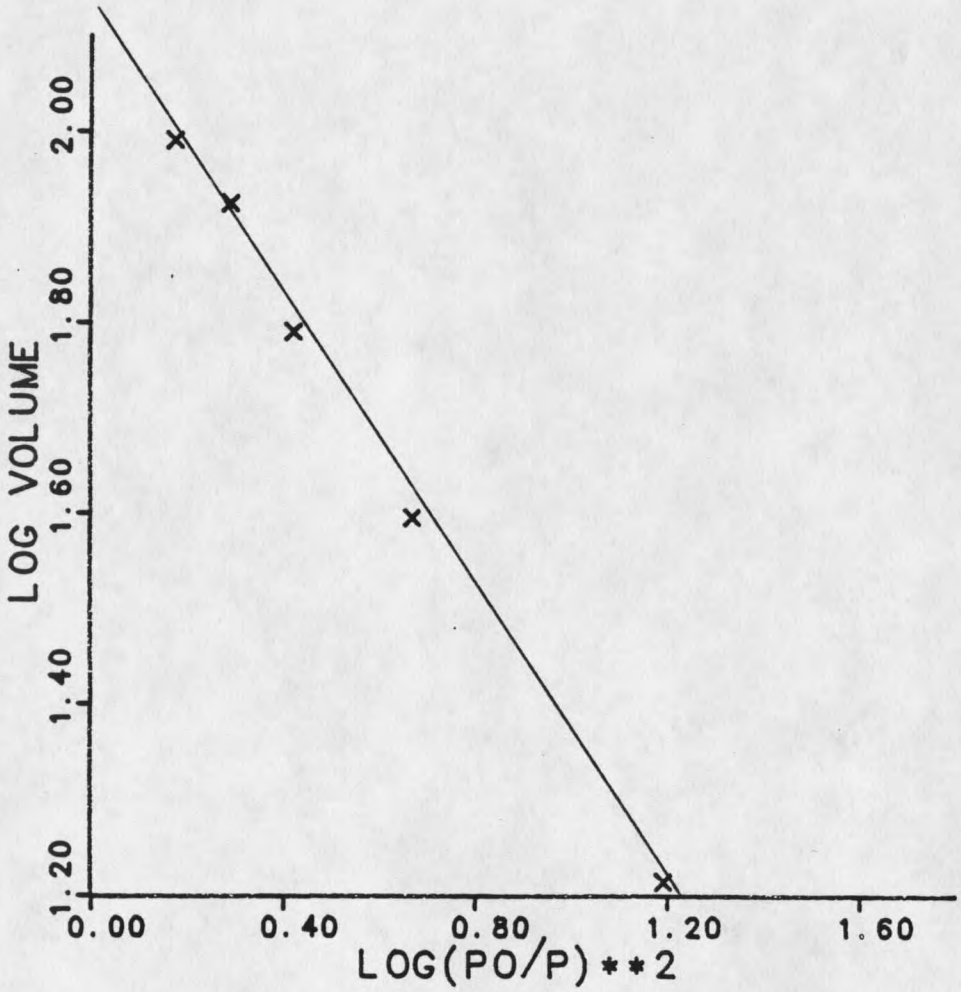

Figure 24. Dubinin-Polanyi plot for methane adsorption on coal sample E83-28 dry.

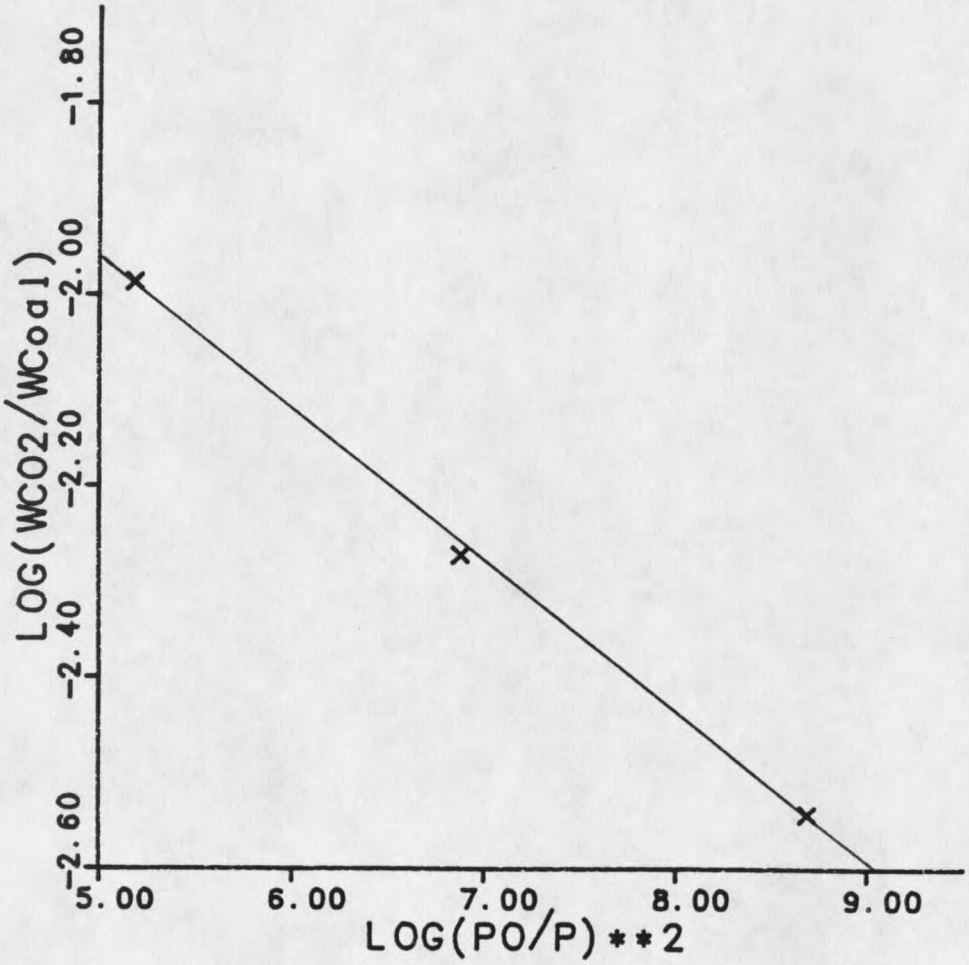

Figure 25. Dubinin-Polanyi plot for carbon dioxide adsorption, done at MSU, on coal sample E83-20.

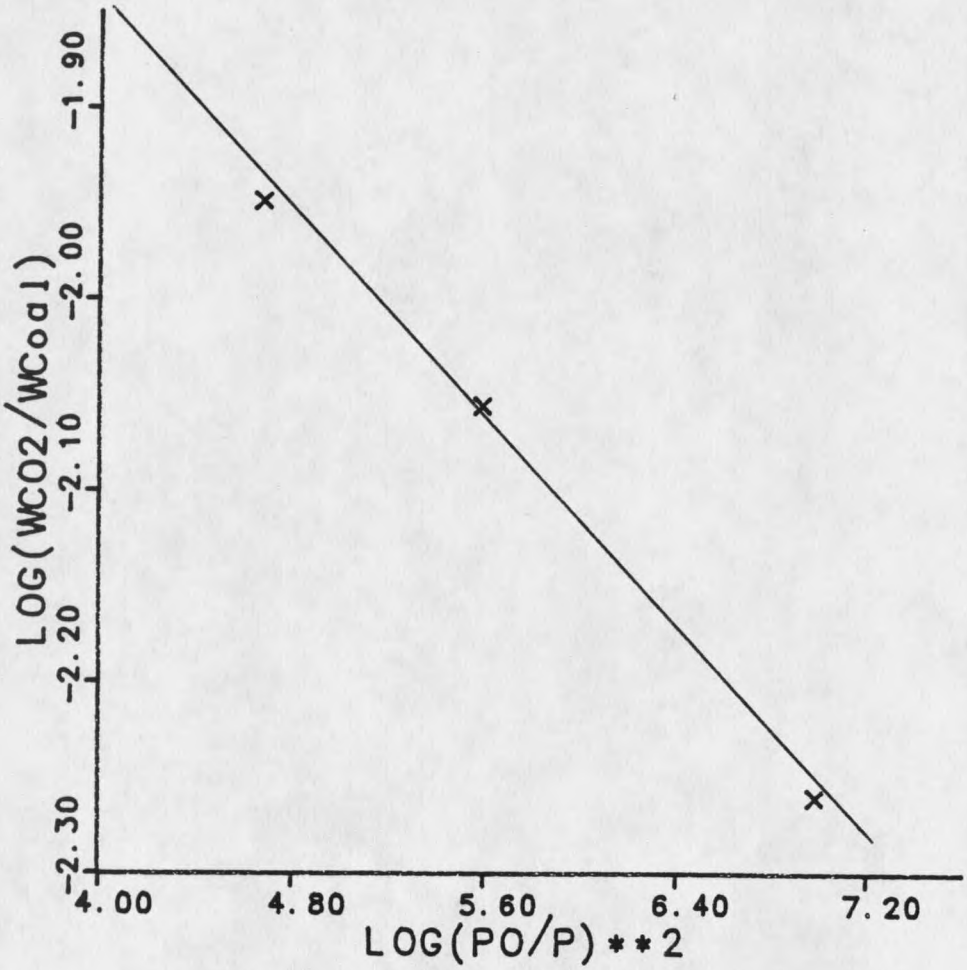

Figure 26. Dubinin-Polanyi plot for carbon dioxide adsorption, done at MSU, on coal sample E83-24.

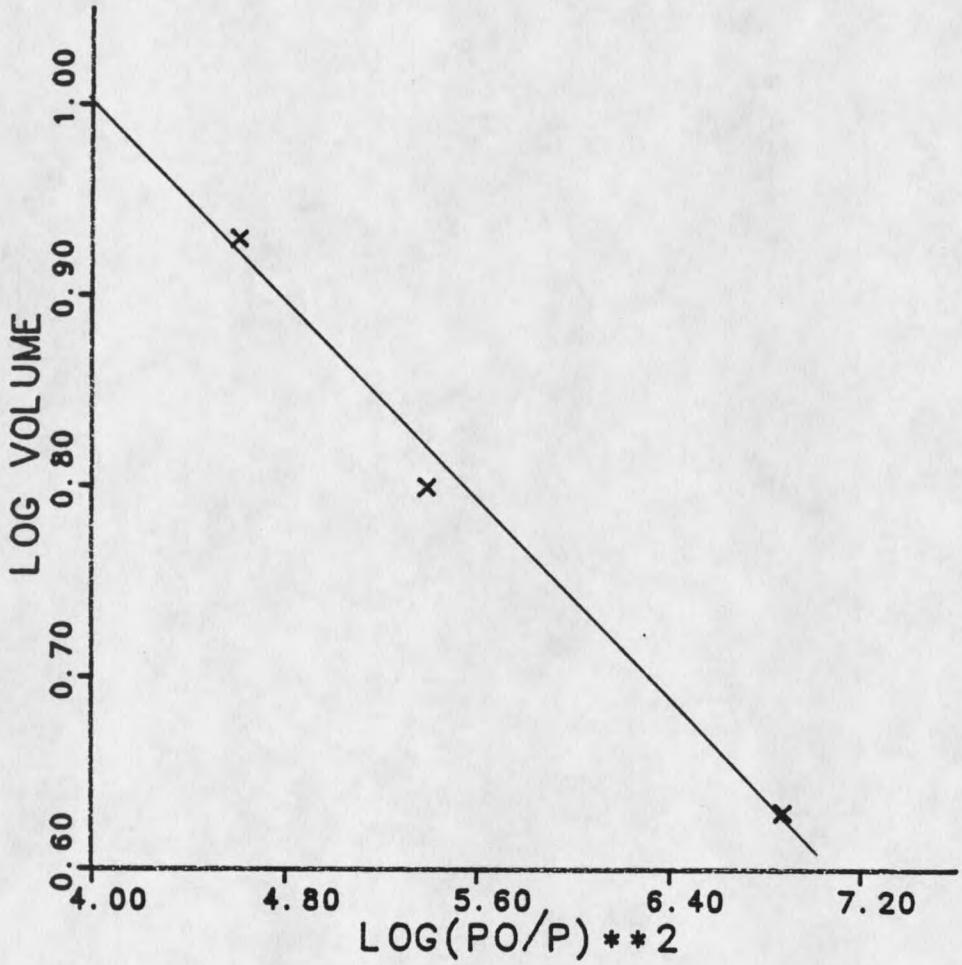

Figure 27. Dubinin-Polanyi plot for carbon dioxide adsorption, done at NMU, on coal sample E83-20.

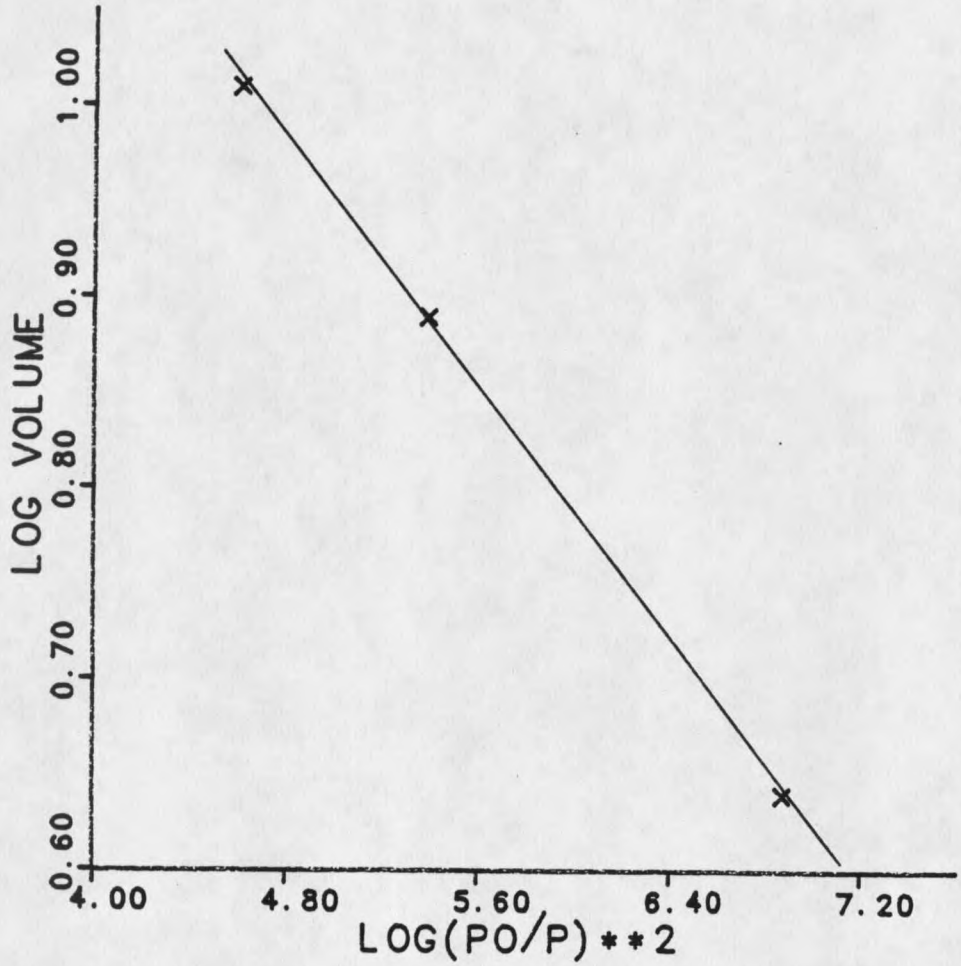

Figure 28. Dubinin-Polanyi plot for carbon dioxide adsorption, done at NMU, on coal sample E83-24.

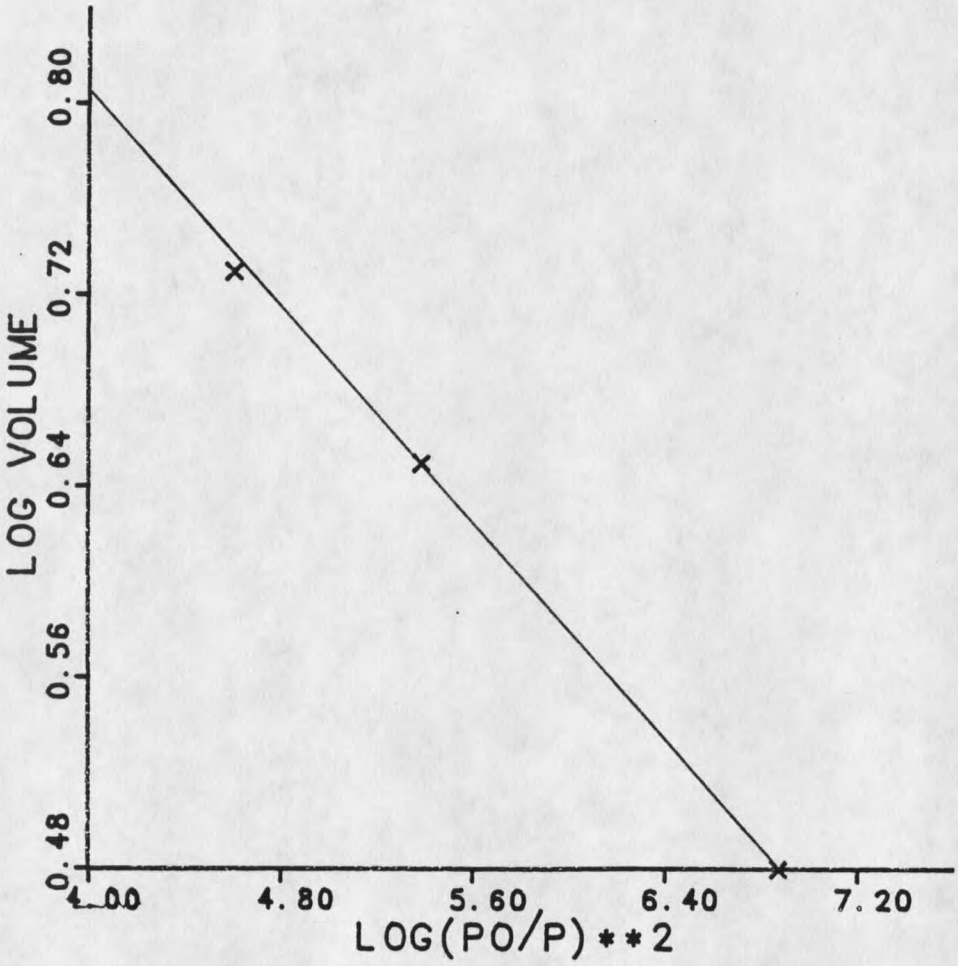

Figure 29. Dubinin-Polanyi plot for carbon dioxide adsorption, done at NMU, on coal sample E83-28.

APPENDIX B

PROGRAMS USED TO MAKE VOLUMETRIC CALIBRATIONS FOR THE METHANE ADSORPTION APPARATUS AND TO CALCULATE THE QUANTITY OF METHANE ADSORBED, RAW DATA AND RESULTS ARE GIVEN

```
C       BENEDICT-WEBB-RUBIN EQUATION OF STATE
C       FILENAME: VWR.FOR
C       CONSTANTS TAKEN FROM REID, PRUASNITZ, AND SHERWOOD
C       THE PROPERTIES OF GASES AND LIQUIDS.
C       WEGSTEIN'S METHOD OF CONVERGENCE
C       IN CHEMELIB; CALL CONV
        REAL MOLECH4
C       INITIATING SECTION
C       R=UNIVERSAL GAS CONSTANT (LITER*ATM/GMOL*K)
        R=.08205
C       UNITS OF A (LITER/GMOL)**3*ATM
        A=4.94E-2
C       UNITS OF AO (LITER/GMOL)**2*ATM
        AO=1.855
C       UNITS OF B (LITER/GMOL)**2
        B=3.38004E-3
C       UNITS OF BO (LITER/GMOL)
        BO=4.26E-2
C       UNITS OF C (LITER/GMOL)**3*K**2*ATM
        C=2.545+3
C       UNITS OF CO (LITER/GMOL)**2*K**2*ATM
        CO=2.2257E+4
C       UNITS OF ALPHA (LITER/GMOL)**3
        ALPHA=1.24359E-4
C       UNITS OF GAMA (LITER/GMOL)**2
        GAMA=6.0E-3
C       UNITS OF V1 (LITER) V1 IS THE VOLUME OF THE LOW PRESSURE TANK
        V1=1.163
C       N EQUALS A COUNTER
3       N=0
        TYPE*,'ENTER T1 IN DEGREES KELVIN AND P1 IN ATM'
        ACCEPT*,T1,P1
        TYPE*,'ENTER X, AN INITIAL GUESS FOR THE DENSITY IN THE LOW
     *  PRESSURE TANK GMOL/LITER'
        ACCEPT*,X
C       CONVERGENCE SECTION
4       XC=(1/(R*T1))*(P1-(BO*R*T1-AO-(CO/T1**2))*X**2-(B*R*T1-A)*X**3-
     *  A*ALPHA*X**6-(C*X**3/T1**2*(1+GAMA*X**2)*EXP(-GAMA*X**2)))
        CALL CONV(X,XC,1,NC)
        N=N+1
        IF(N.EQ.50)GO TO 5
5       MOLECH4=XC*V1
        WRITE(10,222)
222     FORMAT(3X,'X=XC=DENSITY OF CH4 IN THE LOW PRESS TANK GMOL/
     *  LITER')
        WRITE(10,666)
666     FORMAT(3X,'MOLECH4=THE GMOLS OF METHANE IN THE LOW PRESS
     *  TANK AT T1 AND P1')
        WRITE(6,111)X,XC,N,MOLECH4
        WRITE(10,111)X,XC,N,MOLECH4
```

```
111     FORMAT(3X,'X= ',F8.3,'XC= ',F8.3,'N= ',I2,'MOLECH4=',F8.3)
        TYPE*,'ENTER T2 IN DEGREES KELVIN AND P2 IN ATM'
        ACCEPT*,T2,P2
        TYPE*,'ENTER W, AN INITIAL GUESS FOR THE DENSITY IN THE HIGH
     *  PRESSURE TANK GMOL/LITER'
        ACCEPT*,W
6       WC=(1/(R*T2))*(P2-(BO*R*T2-AO-(CO/T2**2))*W**2-(B*R*T2-A)*W**3-
     *  A*ALPHA*W**6-(C*W**3/T2**2*(1+GAMA*W**2)*EXP(-GAMA*W**2)))
        CALL CONV(W,WC,2,NC)
        GO TO (7,6),NC
7       V2=MOLECH4/WC
        WRITE(10,333)
333     FORMAT(3X,'W=WC=DENSITY OF CH4 IN HIGH PRESS TANK GMOL/
     *  LITER')
        WRITE(10,555)
555     FORMAT(3X,'V2=THE VOLUME OF THE HIGH PRESS TANK')
        WRITE(6,444)W,WC,V2
        WRITE(10,444)W,WC,V2
444     FORMAT(3X,'W= ',F8.3,'WC= ',F8.3,'V2= ',F8.3)
        WRITE(10,777)
777     FORMAT(3X,'P1 AND T1 ARE THE TEMP AND PRESSURE OF THE LOW
     *  PRESS TANK WHILE P2 AND T2 ARE THE TEMP AND PRESS OF THE
     *  HIGH PRESS TANK')
        WRITE(10,888)T1,P1,T2,P2
888     FORMAT(3X,'T1=',F8.3,'P1=',F8.3,'T2=',F8.3,'P2=',F8.3)
        TYPE*,'DO YOU WANT TO DO ANOTHER RUN? YES-O'
        ACCEPT*,RUN
        IF(RUN.EQ.O)GO TO 3
        END
```

```
C       CALCULATION OF CH4 ADSORBED
C       BENEDICT-WEBB-RUBIN EQUATION OF STATE
C       FILENAME: COAL.FOR
C       CONSTANTS TAKEN FROM REID, PRUASNITZ, AND SHERWOOD
C       THE PROPERTIES OF GASES AND LIQUIDS.
C       WEGSTEIN'S METHOD OF CONVERGENCE
C       IN CHEMELIB; CALL CONV
        REAL MOLECH4,NEWMOLE
C       INITIATING SECTION
        M=0
        TYPE*,'ENTER V2 IN LITERS'
        ACCEPT*,V2
        TYPE*,'ENTER COAL SAMPLE WEIGHT GRAMS'
        ACCEPT*,SAMP
C       R=UNIVERSAL GAS CONSTANT (LITER*ATM/GMOL*K)
        R=.08205
C       UNITS OF A (LITER/GMOL)**3*ATM
        A=4.94E-2
C       UNITS OF AO (LITER/GMOL)**2*ATM
        AO=1.855
C       UNITS OF B (LITER/GMOL)**2
        B=3.38004E-3
C       UNITS OF BO (LITER/GMOL)
        BO=4.26E-2
C       UNITS OF C (LITER/GMOL)**3*K**2*ATM
        C=2.2257E+4
C       UNITS OF ALPHA (LITER/GMOL)**3
        ALPHA=1.24359E-4
C       UNITS OF GAMA (LITER/GMOL)**2
        GAMA=6.0E-3
C       UNITS OF V1 (LITER) V1 IS THE VOLUME OF THE LOW PRESSURE TANK
        V1=1.1631
C       N EQUALS A COUNTER
2       N=0
        TYPE*,'ENTER T1 IN DEGREES KELVIN AND P1 IN ATM'
        ACCEPT*,T1,P1
        TYPE*,'ENTER X, AN INITIAL GUESS FOR THE DENSITY IN THE LOW
     *  PRESSURE TANK GMOL/LITER'
        ACCEPT*,X
C       CONVERGENCE SECTION
4       XC=(1/(R*T1))*(P1-(BO*R*T1-AO-(CO/T1**2))*X**2-(B*R*T1-A)*X**3-
     *  A*ALPHA*X**6-(C*X**3/T1**2*(1+GAMA*X**2)*EXP(-GAMA*X**2)))
        CALL CONV(X,XC,1,NC)
        N=N+1
        IF(N.EQ.50)GO TO 5
        GO TO (5,4),NC
5       IF(M.NE.0)GO TO 1
        MOLECH4=XC*V1
        GO TO 9
```

```
1       MOLECH4=MOLECH4+XC*V1
9       WRITE(10,222)
222     FORMAT(3X,'X=SC=DENSITY OF CH4 IN THE LOW PRESS TANK GMOL/
     *  LITER')
        WRITE(10,666)
666     FORMAT(3X,'MOLECH4= THE GMOLS OF METHANE IN THE LOW PRESS
     *  TANK AT T1 AND P1')
        WRITE(6,111)X,XC,N,MOLECH4
        WRITE(10,111)X,XC,N,MOLECH4
111     FORMAT(3X,'X= ',F8.3,'XC= ',F8.3,'N= ',I2,'MOLECH4=',F8.3)
        TYPE*,'ENTER T2 IN DEGREES KELVIN AND P2 IN ATM'
        ACCEPT*,T2,P2
        TYPE*,'ENTER W, AN INITIAL GUESS FOR THE DENSITY IN THE HIGH
     *  PRESSURE TANK GMOL/LITER'
        ACCEPT*,W
6       WC=(1/(R*T2))*(P2-(BO*R*T2-AO-(CO/T2**2))*W**2-(B*R*T2-A)*W**3-
     *  A*ALPHA*W**6-(C*W**3/T2**2*(1+GAMA*W**2)*EXP(-GAMA*W**2)))
        CALL CONV(W,WC,2,NC)
        GO TO (7,6),NC
7       NEWMOLE=V2*WC
        WRITE(10,333)
333     FORMAT(3X,'W=WC=DENSITY OF CH4 IN HIGH PRESS TANK GMOL/
     *  LITER')
        WRITE(10,555)
555     FORMAT(3X,'V2= THE VOLUME OF THE HIGH PRESS TANK')
        WRITE(6,444)W,WC,V2
        WRITE(10,444)W,WC,V2
444     FORMAT(3X,'W= ',F8.3,'WC= ',F8.3,'V2= ',F8.3)
        WRITE(6,999)
        WRITE(10,9990
999     FORMAT(3X,'NEWMOLE MOLES IN VOID SPACE')
        WRITE(6,998)NEWMOLE
        WRITE(10,998)NEW MOLE
998     FORMAT(3X,'NEWMOLE=',F10.5)
C       MOLES CH4 ADSORBED
        ADS=(MOLECH4-NEWMOLE)
C       TIC=GRAMOLESCH4/GRAM COAL
        TIC=ADS/SAMP
        WRITE(6,997)
        WRITE(10,997)
997     FORMAT(3X,'TIC MOLES CH4 ADSORBED PER GRAM OF COAL')
        WRITE(6,996)TIC
        WRITE(10,996)TIC
996     FORMAT(3X,'TIC=',F10.5)
        B1=TIC*22.41*1000
        WRITE(6,155)
        WRITE(10,155)
155     FORMAT(3X,'B1 IS CUBIC CENTIMETERS OF CH4 PER GRAM OF COAL
     *  AT STP')
        WRITE(6,156)B1
        WRITE(10,156)B1
```

```
156     FORMAT(3X,'B1=',F15.10)
        B2=B1*32.0335
        WRITE(6,157)
        WRITE(10,157)
157     FORMAT(3X,MB2 IS CUBIC FEET OF CH4 PER TON OF COAL AT STP')
        WRITE(6,158)B2
        WRITE(10,158)B2
158     FORMAT(3X,MB2=',F15.5)
        WRITE(10,777)
777     FORMAT(3X,'P1 and T1 ARE THE TEMP AND PRESSURE OF THE LOW
     *  PRESS TANK WHILE P2 AND T2 ARE THE TEMP AND PRESS OF THE
     *  HIGH PRESS TANK')
        WRITE(10,888)T1,P1,T2,P2
888     FORMAT(3X,'T1=',F8.3,'P1=',F8.3,'T1=',F8.3,'P2=',F8.3)
        TYPE*,'DO YOU WANT TO DO ANOTHER RUN? YES=0
        ACCEPT*,RUN
        IF(RUN.EQ.0)GO TO 3
        GO TO 18
3       M=M+1
        GO TO 2
18      END
```

X=XC=DENSITY OF CH4 IN THE LOW PRESS TANK GMOL/LITER
MOLECH4= THE GMOLS OF METHANE IN THE LOW PRESS TANK AT T1 AND P1
X= 0.123XC= 0.123N= 3MOLECH4= 0.143
W=WC=DENSITY OF CH4 IN HIGH PRESS TANK GMOL/LITER
V2= THE VOLUME OF THE HIGH PRESS TANK
W= 1.007WC= 1.007V2= 0.138
NEWMOLE MOLES IN VOID SPACE
NEWMOLE= 0.13888
TIC MOLES CH4 ADSORBED PER GRAM OF COAL
TIC= 0.00029
B1 IS CUBIC CENTIMETERS OF CH4 PER GRAM OF COAL AT STP
B1= 6.4253859520
B2 IS CUBIC FEET OF CH4 PER TON OF COAL AT STP
B2= 205.82761
P1 AND T1 ARE THE TEMP AND PRESSURE OF THE LOW PRESS TANK WHILE P2 AND T2 ARE THE TEMP AND PRESS OF THE HIGH PRESS TANK
T1= 297.000P1= 2.970T2= 297.000P2= 23.520
X=XC=DENSITY OF CH4 IN THE LOW PRESS TANK GMOL/LITER
MOLECH4= THE GMOLS OF METHANE IN THE LOW PRESS TANK AT T1 AND P1
X= 0.131XC= 0.131N= 3MOLECH4= 0.295
W=WC=DENSITY OF CH4 IN HIGH PRESS TANK GMOL/LITER
V2= THE VOLUME OF THE HIGH PRESS TANK
W= 2.076WC= 2.076V2= 0.138
NEWMOLE MOLES IN VOID SPACE
NEWMOLE= 0.28628
TIC MOLES CH4 ADSORBED PER GRAM OF COAL
TIC= 0.00068
B1 IS CUBIC CENTIMETERS OF CH4 PER GRAM OF COAL AT STP
B1= 15.2501850128
B2 IS CUBIC FEET OF CH4 PER TON OF COAL AT STP
B2= 488.51682
P1 AND T1 ARE THE TEMP AND PRESSURE OF THE LOW PRESS TANK WHILE P2 AND T2 ARE THE TEMP AND PRESS OF THE HIGH PRESS TANK
T1= 297.500P1= 3.180T2= 299.000P2= 46.920
X=XC=DENSITY OF CH4 IN THE LOW PRESS TANK GMOL/LITER
MOLECH4= THE GMOLS OF METHANE IN THE LOW PRESS TANK AT T1 AND P1
X= 0.128XC= 0.128N= 3MOLECH4= 0.444
W=WC=DENSITY OF CH4 IN HIGH PRESS TANK GMOL/LITER
V2= THE VOLUME OF THE HIGH PRESS TANK
W= 3.126WC= 3.126V2= 0.138
NEWMOLE MOLES IN VOID SPACE
NEWMOLE= 0.43115
TIC MOLES CH4 ADSORBED PER GRAM OF COAL
TIC= 0.00098
B1 IS CUBIC CENTIMETERS OF CH4 PER GRAM OF COAL AT STP
B1= 22.0703067780
B2 IS CUBIC FEET OF CH4 PER TON OF COAL AT STP
B2= 706.98920
P1 AND T1 ARE THE TEMP AND PRESSURE OF THE LOW PRESS TANK WHILE P2 AND T2 ARE THE TEMP AND PRESS OF THE HIGH PRESS TANK

T1= 299.000P1= 3.120T2= 298.000P2= 67.940
X=XC=DENSITY OF CH4 IN THE LOW PRESS TANK GMOL/LITER
MOLECH4= THE GMOLS OF METHANE IN THE LOW PRESS TANK AT T1 AND P1
X= 0.133XC= 0.133N= 3MOLECH4= 0.599
W=WC=DENSITY OF CH4 IN HIGH PRESS TANK GMOL/LITER
V2= THE VOLUME OF HIGH PRESS TANK
W= 4.230WC= 4.230V2= 0.138
NEWMOLE MOLES IN VOID SPACE
NEWMOLE= 0.58329
TIC MOLES CH4 ADSORBED PER GRAM OF COAL
TIC= 0.00121
B1 IS CUBIC CENTIMETERS OF CH4 PER GRAM OF COAL AT STP
B1= 27.1700553894
B2 IS CUBIC FEET OF CH4 PER TON OF COAL AT STP
B2= 870.35199
P1 AND T1 ARE THE TEMP AND PRESSURE OF THE LOW PRESS TANK WHILE
P2 AND T2 ARE THE TEMP AND PRESS OF THE HIGH PRESS TANK
T1= 298.000P1= 3.240T2= 298.000P2= 89.090
X=XC=DENSITY OF CH4 IN THE LOW PRESS TANK GMOL/LITER
MOLECH4= THE GMOLS OF METHANE IN THE LOW PRESS TANK AT T1 AND P1
X= 0.150XC= 0.150N= 3MOLECH4= 0.773
W=WC=DENSITY OF CH4 IN HIGH PRESS TANK GMOL/LITER
V2= THE VOLUME OF THE HIGH PRESS TANK
W= 5.467WC= 5.467V2= 0.138
NEWMOLE MOLES IN VOID SPACE
NEWMOLE= 0.75398
TIC MOLES CH4 ADSORBED PER GRAM OF COAL
TIC= 0.00153
B1 IS CUBIC CENTIMETERS OF CH4 PER GRAM OF COAL AT STP
B1= 34.3553848267
B2 IS CUBIC FEET OF CH4 PER TON OF COAL AT STP
B2= 1100.52319
P1 AND T1 ARE THE TEMP AND PRESSURE OF THE LOW PRESS TANK WHILE
P2 AND T2 ARE THE TEMP AND PRESS OF THE HIGH PRESS TANK
T1= 298.000P1= 3.650T2= 298.000P2= 112.090
X=XC=DENSITY OF CH4 IN THE LOW PRESS TANK GMOL/LITER
MOLECH4= THE GMOLS OF METHANE IN THE LOW PRESS TANK AT T1 AND P1
X= 0.178XC= 0.178N= 3MOLECH4= 0.980
W=WC=DENSITY OF CH4 IN HIGH PRESS TANK GMOL/LITER
V2= THE VOLUME OF THE HIGH PRESS TANK
W= 6.955WC= 6.955V2= 0.138
NEWMOLE MOLES IN VOID SPACE
NEWMOLE= 0.95916
TIC MOLES CH4 ADSORBED PER GRAM OF COAL
TIC= 0.00167
B1 IS CUBIC CENTIMETERS OF CH4 PER GRAM OF COAL AT STP
B1= 37.3189659119
B2 IS CUBIC FEET OF CH4 PER TON OF COAL AT STP
B2= 1195.45715
P1 AND T1 ARE THE TEMP AND PRESSURE OF THE LOW PRESS TANK WHILE
P2 AND T2 ARE THE TEMP AND PRESS OF THE HIGH PRESS TANK
T1= 299.000P1= 4.330T2= 300.000P2= 141.480

Table 6. Raw Data Used to Determine the Volume of Methane Adsorbed for Coal Sample E83-24 Wet.*

	Run #					
	1	2	3	4	5	6
Tank 1 Pressure (Atm)	2.29	2.97	2.97	3.11	3.04	3.45
Tank 1 Temperature (Kelvin)	296.0	296.0	297.0	297.0	297.0	297.0
Tank 2 Pressure (Atm)	18.82	40.32	61.14	82.36	101.95	121.5
Tank 2 Temperature (Kelvin)	295.5	296.0	297.0	297.0	297.0	294.0
Volume Adsorbed (Ft^3/ton)	100.2	535.6	819.2	909.0	1098.1	1377.7

*The standard deviations of these data are ± 0.14 atm and ± 1.0 degree Kelvin.

Table 7. Raw Data Used to Determine the Volume of Methane Adsorbed for Coal Sample E83-28 Wet.*

	Run #					
	1	2	3	4	5	6
Tank 1 Pressure (Atm)	2.70	3.18	3.04	3.31	3.45	
Tank 1 Temperature (Kelvin)	297.0	297.0	296.0	296.0	295.0	
Tank 2 Pressure (Atm)	21.27	43.99	64.49	86.85	109.03	
Tank 2 Temperature (Kelvin)	297.0	296.0	296.0	295.0	295.0	
Volume Adsorbed (Ft^3/ton)	308.4	742.9	1126.7	1082.47	1217.2	

*The standard deviations of these data are ± 0.14 atm and ± 1.0 degree Kelvin.

Table 8. Raw Data Used to Determine the Volume of Methane Adsorbed for Coal Sample E83-20 Dry.*

	Run #					
	1	2	3	4	5	6
Tank 1 Pressure (Atm)	2.50	3.18	3.11	3.93	3.99	4.20
Tank 1 Temperature (Kelvin)	297.0	296.5	296.0	295.0	294.0	293.0
Tank 2 Pressure (Atm)	18.96	41.27	61.95	83.86	110.39	131.07
Tank 2 Temperature (Kelvin)	296.0	296.0	295.0	294.0	293.0	292.0
Volume Adsorbed (Ft^3 /ton)	468.1	1106.6	1555.8	2914.7	2532.4	4329.4

*The standard deviations of these data are ± 0.14 atm and ± 1.0 degree Kelvin.

Table 9. Raw Data Used to Determine the Volume of Methane Adsorbed for Coal Sample E83-24 Dry.*

	Run #					
	1	2	3	4	5	6
Tank 1 Pressure (Atm)	3.04	3.18	3.11	3.18	4.06	3.86
Tank 1 Temperature (Kelvin)	300.0	299.0	300.0	300.0	300.0	299.0
Tank 2 Pressure (Atm)	24.88	48.75	69.77	91.48	116.51	143.56
Tank 2 Temperature (Kelvin)	299.0	300.0	300.0	300.0	299.0	300.0
Volume Adsorbed (Ft^3 /ton)	0.0	65.9	372.1	265.3	587.5	282.1

*The standard deviations of these data are ± 0.14 atm and ± 1.0 degree Kelvin.

Table 10. Raw Data Used to Determine the Volume of Methane Adsorbed for Coal Sample E83-28 Dry.*

	Run #					
	1	2	3	4	5	6
Tank 1 Pressure (Atm)	2.97	2.97	3.04	3.04	3.99	3.79
Tank 1 Temperature (Kelvin)	294.0	294.0	292.0	295.0	294.0	296.0
Tank 2 Pressure (Atm)	22.56	42.36	62.56	80.59	106.31	128.20
Tank 2 Temperature (Kelvin)	294.0	292.0	295.0	294.0	296.0	295.0
Volume Adsorbed (Ft^3/ton)	525.1	1265.9	1983.3	2699.3	3148.6	3770.4

*The standard deviations of these data are ± 0.14 atm and ± 1.0 degree Kelvin.

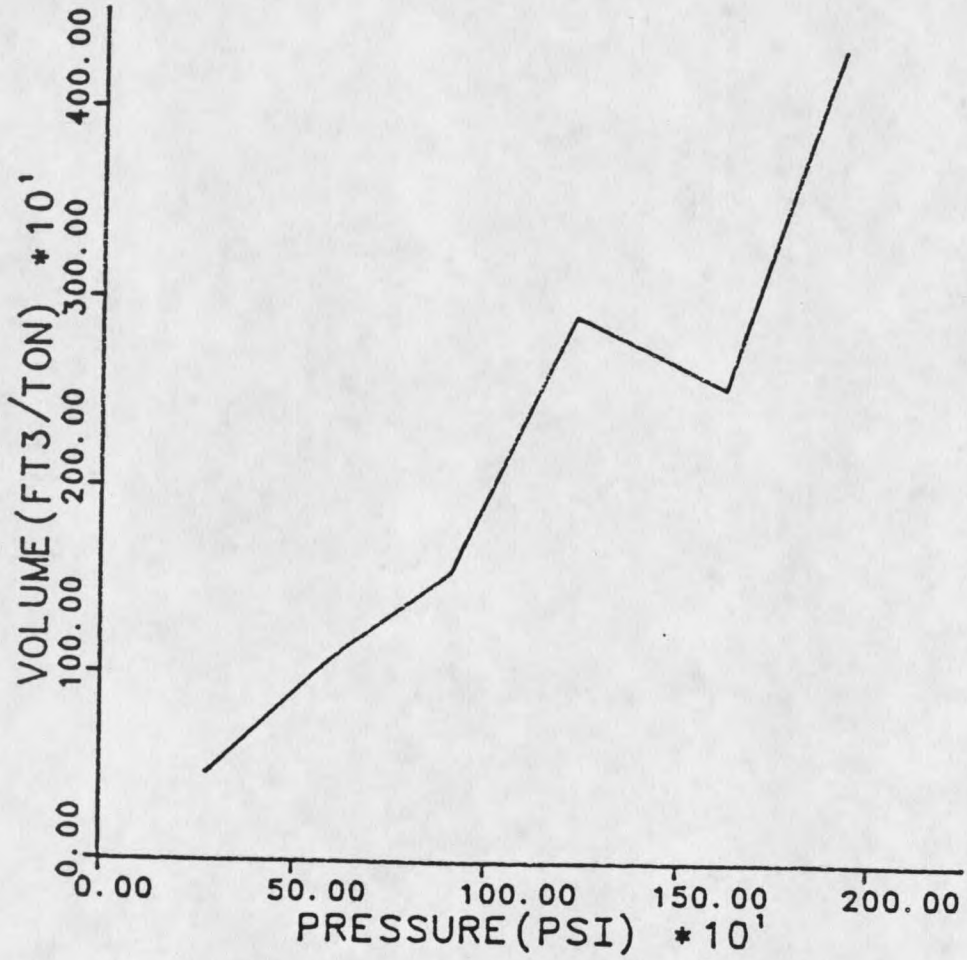

Figure 30. Pressure versus volume of methane adsorbed for coal sample E83-20 dry, no points have been omitted.

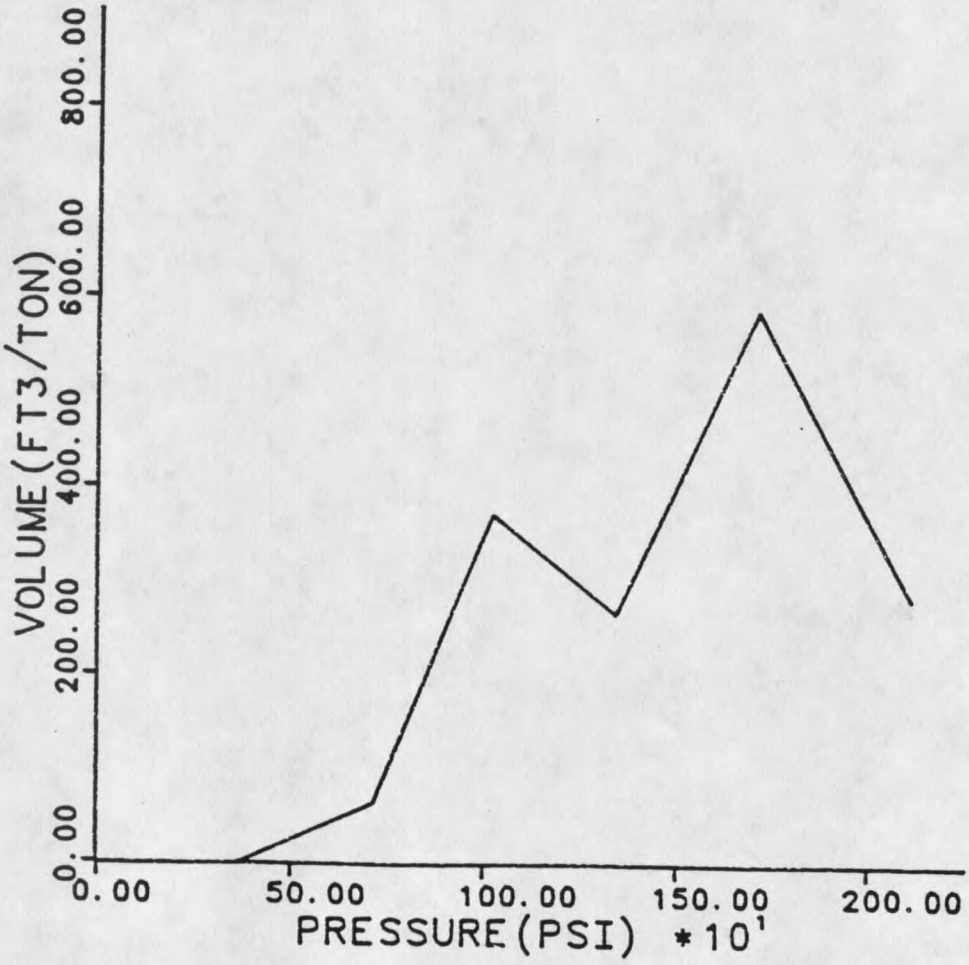

Figure 31. Pressure versus volume of methane adsorbed for coal sample E83-24 dry, no points have been omitted.

APPENDIX C

RAW MERCURY POROSIMETER DATA AND CURVES GENERATED THAT ARE NOT PRESENTED IN THE TEXT

Table 11. Raw Mercury Porosimeter Data for Coal Sample E83-20. Corresponding Radius and Distribution are Also Listed.

Pressure psia	Volume cc/g	Radius microns	Distribution cm^3/micron
364.8	0.0003	0.292489	0.0135
397.8	0.0006	0.268225	0.0149
433.2	0.0009	0.246307	0.0057
469.8	0.0010	0.227118	0.0270
505.2	0.0014	0.211203	0.0301
541.8	0.0018	0.196936	0.0082
580.2	0.0019	0.183902	0.0273
619.8	0.0022	0.172152	0.0313
658.8	0.0025	0.161961	0.0111
700.2	0.0026	0.152385	0.0162
768.6	0.0028	0.138824	0.0937
787.2	0.0031	0.135544	0.0485
826.8	0.0034	0.129052	0.0171
868.2	0.0035	0.122898	0.0411
927.0	0.0038	0.115102	0.0276
994.2	0.0040	0.107322	0.0946
1014.6	0.0042	0.105165	0.0534
1053.6	0.0044	0.101272	0.0783
1096.8	0.0047	0.098283	0.0464
1150.2	0.0049	0.092766	0.0710
1187.4	0.0051	0.089860	0.0509
1244.4	0.0053	0.085744	0.0513
1306.8	0.0055	0.081650	0.0833
1326.6	0.0056	0.080431	0.0883
1366.2	0.0058	0.078100	0.1040
1420.8	0.0061	0.075099	0.0314
1486.8	0.0062	0.071765	0.2029
1507.8	0.0064	0.070765	0.0660
1578.6	0.0066	0.067592	0.1003
1602.6	0.0067	0.066579	0.0765
1671.0	0.0069	0.063854	0.0477
1729.8	0.0070	0.061683	0.2345
1754.4	0.0072	0.060819	0.0519
1813.8	0.0073	0.058827	0.1972
1846.2	0.0075	0.057794	0.1280
1899.0	0.0077	0.056187	0.0611
1957.8	0.0078	0.054500	0.0642
2017.2	0.0079	0.052895	0.3607
2038.8	0.0081	0.052335	0.1291
2103.0	0.0083	0.050737	0.1343
2134.8	0.0084	0.049981	0.0790
2191.8	0.0085	0.048681	0.2503
2229.0	0.0087	0.047869	0.0842
2287.2	0.0088	0.046651	0.1508
2356.2	0.0090	0.045285	0.2159

Table 11 (continued).

Pressure psia	Volume cc/g	Radius microns	Distribution cm^3/micron
2380.8	0.0091	0.044817	0.0977
2437.8	0.0092	0.043769	0.3186
2473.8	0.0094	0.043132	0.1771
2542.2	0.0096	0.041972	0.0958
2608.8	0.0097	0.040900	0.2642
2633.4	0.0098	0.040518	0.1178
2691.0	0.0099	0.039651	0.2087
2759.4	0.0101	0.038668	0.0000
2782.8	0.0101	0.038343	0.2549
2842.2	0.0103	0.037541	0.2606
2902.8	0.0105	0.036758	0.0000
2965.2	0.0105	0.035984	0.3382
3015.6	0.0107	0.035383	0.3439
3040.8	0.0108	0.035089	0.3063
3099.6	0.0110	0.034424	0.1375
3168.0	0.0111	0.033681	0.3792
3193.2	0.0112	0.033415	0.3546
3249.0	0.0114	0.032841	0.0000
3319.2	0.0114	0.032146	0.3312
3384.0	0.0116	0.031531	0.4039
3411.0	0.0117	0.031281	0.3133
3483.6	0.0119	0.030629	0.4015
3512.4	0.0120	0.030378	0.1937
3574.2	0.0121	0.029853	0.3797
3639.6	0.0123	0.029316	0.0000
3700.2	0.0123	0.028836	0.4930
3726.6	0.0124	0.028632	0.4660
3784.2	0.0126	0.028196	0.0000
3843.0	0.0126	0.027765	0.4193
3911.4	0.0128	0.027279	0.5384
3938.4	0.0129	0.027092	0.4399
4006.8	0.0131	0.026630	0.3431
4147.8	0.0134	0.025724	0.3375
4302.0	0.0137	0.024802	0.4224
4432.8	0.0140	0.024071	0.4496
4563.0	0.0143	0.023384	0.1845
4674.0	0.0144	0.022828	0.6189
4814.4	0.0148	0.022163	0.3732
4936.8	0.0150	0.021613	0.5021
5081.4	0.0153	0.020998	0.5352
5224.8	0.0156	0.020422	0.8145
5322.6	0.0159	0.020047	0.6230
5457.0	0.0162	0.019553	0.2418
5577.6	0.0163	0.019130	0.6392
5721.6	0.0166	0.018649	0.7772
5845.2	0.0169	0.018254	0.6815

Table 11 (continued).

Pressure psia	Volume cc/g	Radius microns	Distribution cm^3/micron
5993.4	0.0172	0.017803	0.5106
6131.4	0.0174	0.017402	0.8697
6258.0	0.0177	0.017050	0.6447
6376.2	0.0179	0.016734	0.8906
6510.0	0.0182	0.016390	0.6292
6641.4	0.0184	0.016066	0.9483
6777.6	0.0187	0.015743	0.9392
6921.0	0.0190	0.015417	0.9945
7062.0	0.0193	0.015109	0.8257
7179.0	0.0195	0.014863	0.7623
7310.4	0.0197	0.014596	0.8582
7431.0	0.0199	0.014359	1.3988
7585.2	0.0203	0.014067	0.8570
7715.4	0.0205	0.013829	0.9543
7836.0	0.0207	0.013617	1.2434
7980.0	0.0210	0.013371	1.1055
8091.0	0.0212	0.013187	1.4340
8223.6	0.0215	0.012975	0.9659
8359.2	0.0217	0.012764	1.5223
8492.4	0.0220	0.012564	1.1153
8617.2	0.0222	0.012382	1.2325
8793.6	0.0225	0.012134	1.8348
8915.4	0.0228	0.011968	1.6560
9054.6	0.0231	0.011784	1.2959
9176.4	0.0233	0.011628	1.2933
9301.8	0.0235	0.011471	1.3101
9429.0	0.0237	0.011316	2.2932
9540.6	0.0240	0.011184	1.2617
9679.8	0.0242	0.011023	1.4382
9937.2	0.0246	0.010737	3.7562
10089.6	0.0252	0.010575	-0.8604
10203.0	0.0251	0.010458	2.3674
10373.4	0.0255	0.010286	1.5955
10503.0	0.0257	0.010159	1.5315
10641.6	0.0259	0.010027	1.6055
10777.2	0.0261	0.009901	2.5691
10907.4	0.0264	0.009782	1.7779
11035.8	0.0266	0.009669	2.2408
11139.6	0.0268	0.009578	2.4269
11287.2	0.0271	0.009453	1.8865
11552.4	0.0275	0.009236	3.1922
11672.4	0.0278	0.009141	1.0861
11792.4	0.0279	0.009048	2.0373
11923.2	0.0281	0.008949	2.9513
12061.8	0.0284	0.008846	2.0745
12196.2	0.0286	0.008749	2.4168

Table 11 (continued).

Pressure psia	Volume cc/g	Radius microns	Distribution cm^3/micron
12313.8	0.0288	0.008665	2.9698
12460.8	0.0291	0.008563	2.4247
12583.2	0.0293	0.008480	2.2459
12718.2	0.0295	0.008390	3.7514
12841.8	0.0298	0.008309	1.2168
12971.4	0.0299	0.008226	3.7068
13101.6	0.0302	0.008144	3.5562
13240.2	0.0305	0.008059	2.0058
13408.2	0.0307	0.007958	3.5607
13504.2	0.0309	0.007901	2.5942
13638.6	0.0311	0.007823	4.0391
13770.6	0.0314	0.007748	4.0626
13904.4	0.0317	0.007674	1.4440
14032.2	0.0318	0.007604	3.5744
14190.6	0.0321	0.007519	2.8126
14327.4	0.0323	0.007447	3.0932
14454.0	0.0325	0.007382	3.1623
14580.0	0.0327	0.007318	5.1032
14739.6	0.0331	0.007239	3.6465
14853.0	0.0333	0.007184	2.9517
14995.8	0.0335	0.007115	3.1109
15133.8	0.0337	0.007050	5.0313
15264.0	0.0340	0.006990	2.0505
15372.0	0.0341	0.006941	5.3849
15497.4	0.0344	0.006885	3.8669
15615.6	0.0346	0.006833	5.3297
15746.4	0.0349	0.006776	1.6708
15888.0	0.0350	0.006716	5.8550
16053.0	0.0354	0.006647	1.9470
16179.0	0.0355	0.006595	6.9058
16287.0	0.0358	0.006551	2.1233
16405.8	0.0359	0.006504	5.8518
16537.2	0.0362	0.006452	6.0263
16666.8	0.0365	0.006402	3.2768
16828.8	0.0367	0.006340	3.9269
16966.2	0.0369	0.006289	4.1700
17097.6	0.0371	0.006241	7.0736
17255.4	0.0375	0.006184	0.0000
17326.8	0.0375	0.006158	8.6957
17458.2	0.0379	0.006112	3.2610
17637.0	0.0381	0.006050	3.0890
17732.4	0.0382	0.006017	7.0834
17859.0	0.0385	0.005975	5.2370
18033.6	0.0388	0.005917	5.5007
18145.8	0.0390	0.005880	5.5398
18258.6	0.0392	0.005844	6.5585

Table 11 (continued).

Pressure psia	Volume cc/g	Radius microns	Distribution cm^3/micron
18403.8	0.0395	0.005798	6.3526
18556.2	0.0398	0.005750	3.1619
18659.4	0.0399	0.005718	9.4370
18799.8	0.0403	0.005676	8.2248
18922.2	0.0406	0.005639	2.8180
19042.8	0.0407	0.005603	4.8517
19185.0	0.0409	0.005562	5.1153
19321.8	0.0411	0.005522	5.6531
19447.2	0.0413	0.005487	2.8904
19571.4	0.0414	0.005452	7.1865
19775.4	0.0418	0.005396	5.6413
19840.8	0.0419	0.005378	6.7957
20006.4	0.0422	0.005333	5.7589
20138.4	0.0424	0.005298	8.3053
20277.6	0.0427	0.005262	5.9957
20407.8	0.0429	0.005228	7.2256
20517.0	0.0431	0.005201	5.8197
20654.4	0.0433	0.005166	10.6380
20768.4	0.0436	0.005138	3.2021
20896.2	0.0437	0.005106	8.5038
21042.6	0.0440	0.005071	6.7295
21167.4	0.0442	0.005041	8.7956
21312.6	0.0445	0.005006	3.5351
21434.4	0.0446	0.004978	12.9194
21569.4	0.0450	0.004947	3.5010
21695.4	0.0451	0.004918	12.1181
21843.0	0.0455	0.004885	0.0000
21959.4	0.0455	0.004859	12.8779
22101.6	0.0459	0.004828	4.2110
22211.4	0.0460	0.004804	9.5614
22358.4	0.0463	0.004772	8.1340
22474.8	0.0465	0.004748	9.6328
22624.2	0.0468	0.004716	4.2729
22737.6	0.0469	0.004693	9.0026
22901.4	0.0472	0.004659	8.8951
23013.0	0.0474	0.004637	10.0171
23163.6	0.0477	0.004606	4.3861
23279.4	0.0478	0.004583	10.0512
23433.0	0.0481	0.004553	7.9212
23564.4	0.0483	0.004528	12.5236
23690.4	0.0486	0.004504	6.9648
23843.4	0.0488	0.004475	8.9698
23963.4	0.0490	0.004453	13.6574
24082.8	0.0493	0.004431	4.2011
24213.6	0.0494	0.004407	14.4358
24367.8	0.0498	0.004379	4.8515

Table 11 (continued).

Pressure psia	Volume cc/g	Radius microns	Distribution cm^3/micron
24483.6	0.0499	0.004358	11.1540
24636.6	0.0502	0.004331	8.4457
24772.8	0.0504	0.004307	9.8251
24891.0	0.0506	0.004287	12.6618
24983.4	0.0508	0.004271	13.6197
25113.6	0.0511	0.004249	8.1364
25260.6	0.0513	0.004224	10.0621
25380.6	0.0515	0.004204	8.8072
25519.2	0.0517	0.004181	11.7034
25677.6	0.0520	0.004155	5.2760
25795.8	0.0521	0.004126	13.3583
25937.4	0.0524	0.004114	6.0534
26042.4	0.0525	0.004097	14.1887
26178.2	0.0528	0.004076	4.6899
26316.6	0.0529	0.004054	20.5130
26444.4	0.0533	0.004035	4.9480
26578.2	0.0534	0.004015	14.4180
26717.4	0.0537	0.003994	5.1885
26847.6	0.0538	0.003974	21.4447
26974.8	0.0542	0.003956	5.5949
27097.8	0.0543	0.003938	14.3716
27243.0	0.0546	0.003917	5.9358
27361.2	0.0547	0.003900	14.7715
27505.2	0.0550	0.003879	5.3039
27640.2	0.0551	0.003860	19.6910
27787.2	0.0555	0.003840	11.8137
27910.8	0.0557	0.003823	11.7493
28036.2	0.0559	0.003806	5.8716
28162.8	0.0560	0.003789	23.3689
28291.2	0.0564	0.003771	0.0000
28425.0	0.0564	0.003754	21.1610
28569.6	0.0568	0.003735	6.1831
28694.4	0.0569	0.003718	15.8462
28842.0	0.0572	0.003699	6.1835
28969.2	0.0573	0.003683	16.3466
29115.0	0.0576	0.003665	8.5973
29208.0	0.0577	0.003653	17.6981
29344.8	0.0580	0.003636	6.2554
29475.6	0.0581	0.003620	19.3702
29602.8	0.0584	0.003604	11.4709
29747.4	0.0586	0.003587	12.6207
29880.0	0.0588	0.003571	14.3988
30056.4	0.0591	0.003550	10.5871
30136.8	0.0592	0.003541	18.5148
30276.0	0.0595	0.003524	13.3711
30405.6	0.0597	0.003509	13.7375

Table 11 (continued).

Pressure psia	Volume cc/g	Radius microns	Distribution cm^3 /micron
30532.8	0.0599	0.003495	6.7066
30664.2	0.0600	0.003480	16.4320
30826.8	0.0603	0.003461	6.8051
30958.8	0.0604	0.003447	27.7286
31056.6	0.0607	0.003436	6.1579
31204.8	0.0608	0.003419	14.8129
31329.0	0.0610	0.003406	14.3133
31458.6	0.0612	0.003392	19.3405
31603.8	0.0615	0.003376	7.2488
31734.0	0.0616	0.003362	14.2906
31867.2	0.0618	0.003348	12.6592
32019.0	0.0620	0.003332	10.2604
32113.2	0.0621	0.003323	19.4594
32263.6	0.0624	0.003307	7.7183
32391.0	0.0625	0.003294	19.8483
32541.0	0.0628	0.003279	7.3800
32676.6	0.0629	0.003265	20.1980
32826.6	0.0632	0.003250	11.7509
32913.0	0.0633	0.003242	0.0000

Table 12. Raw Mercury Porosimeter Data for Coal Sample E83-24. Corresponding Radius and Distribution are Also Listed.

Pressure psia	Volume cc/g	Radius microns	Distribution cm^3/micron
249.0	0.005	0.428514	0.0153
587.4	0.0021	0.181648	0.0189
932.4	0.0029	0.114436	0.0275
1253.4	0.0035	0.085128	0.0194
1645.2	0.0038	0.064855	0.0544
2519.4	0.0046	0.042351	0.0854
3415.2	0.0053	0.031243	0.0672
4128.0	0.0056	0.025848	0.1051
5453.4	0.0061	0.019566	0.1617
6404.4	0.0065	0.016660	0.1282
7706.4	0.0068	0.013846	0.2014
8356.2	0.0070	0.012769	0.2144
9553.2	0.0073	0.011169	0.1964
10632.0	0.0075	0.010036	0.2063
11923.8	0.0077	0.008948	0.1934
12706.2	0.0078	0.008397	0.2779
14034.6	0.0080	0.007603	0.2034
15082.8	0.0081	0.007074	0.3762
16427.4	0.0083	0.006495	0.4169
17862.0	0.0085	0.005974	0.6194
18948.6	0.0087	0.005631	0.3673
19965.6	0.0088	0.005344	0.5748
20661.6	0.0089	0.005164	0.6324
22110.6	0.0091	0.004826	1.1679
23432.4	0.0094	0.004554	0.5974
24363.6	0.0095	0.004379	1.0548
25521.0	0.0097	0.004181	1.2479
26582.4	0.0099	0.004014	1.0881
27925.8	0.0101	0.003821	1.4079
28465.2	0.0102	0.003748	1.0577
29221.8	0.0103	0.003651	1.2265
29905.2	0.0104	0.003568	0.8701
30936.0	0.0105	0.003449	1.0327
31857.0	0.0106	0.003349	1.2771
32638.8	0.0107	0.003269	3.5869
32922.0	0.0108	0.003241	0.0000

Table 13. Raw Mercury Porosimeter Data for Coal Sample E83-28. Corresponding Radius and Distribution are Also Listed.

Pressure psia	Volume cc/g	Radius microns	Distribution cm^3/micron
459.0	0.0001	0.232462	0.0000
767.4	0.0001	0.139041	0.0031
1219.2	0.0002	0.087516	0.0101
1948.8	0.0003	0.054752	0.0101
2549.4	0.0004	0.041853	0.0129
3378.6	0.0005	0.031581	0.0234
4030.2	0.0006	0.026475	0.0284
4785.6	0.0007	0.022296	0.0359
5607.0	0.0008	0.019030	0.0492
6384.0	0.0009	0.016714	0.0496
7427.4	0.0010	0.014366	0.0921
8094.0	0.0011	0.013183	0.0737
9161.4	0.0012	0.011647	0.1175
9951.6	0.0013	0.010722	0.1377
10736.4	0.0014	0.009938	0.1580
11524.2	0.0015	0.009259	0.1286
12699.6	0.0016	0.008402	0.2153
13492.2	0.0017	0.007908	0.1676
14700.6	0.0018	0.007258	0.2900
15474.6	0.0019	0.006895	0.2701
16408.8	0.0020	0.006503	0.2947
17368.2	0.0021	0.006143	0.3544
18249.0	0.0022	0.005847	0.3170
19356.6	0.0023	0.005512	0.4315
20247.0	0.0024	0.005270	0.4095
21283.8	0.0025	0.005013	0.5687
22087.8	0.0026	0.004831	0.4232
23289.0	0.0027	0.004582	0.5363
24322.8	0.0028	0.004387	0.5557
25411.8	0.0029	0.004199	0.8489
26167.8	0.0030	0.004078	0.5343
27493.8	0.0031	0.003881	0.7288
28541.4	0.0032	0.003738	0.6899
29743.2	0.0033	0.003587	1.1154
30526.2	0.0034	0.003495	0.9122
31548.8	0.0035	0.003382	0.9929
32548.8	0.0036	0.003278	2.1300
33028.8	0.0037	0.003231	0.0000

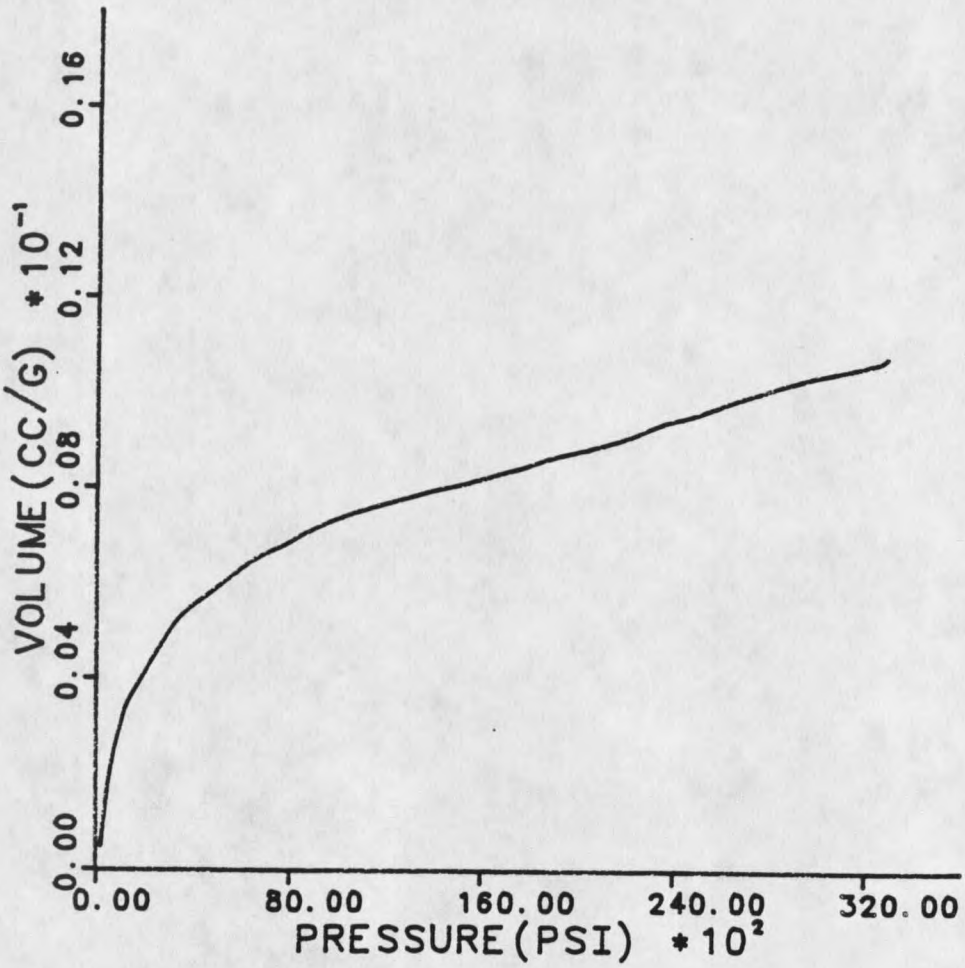

Figure 32. Pressure versus volume of mercury for coal sample E83-24.

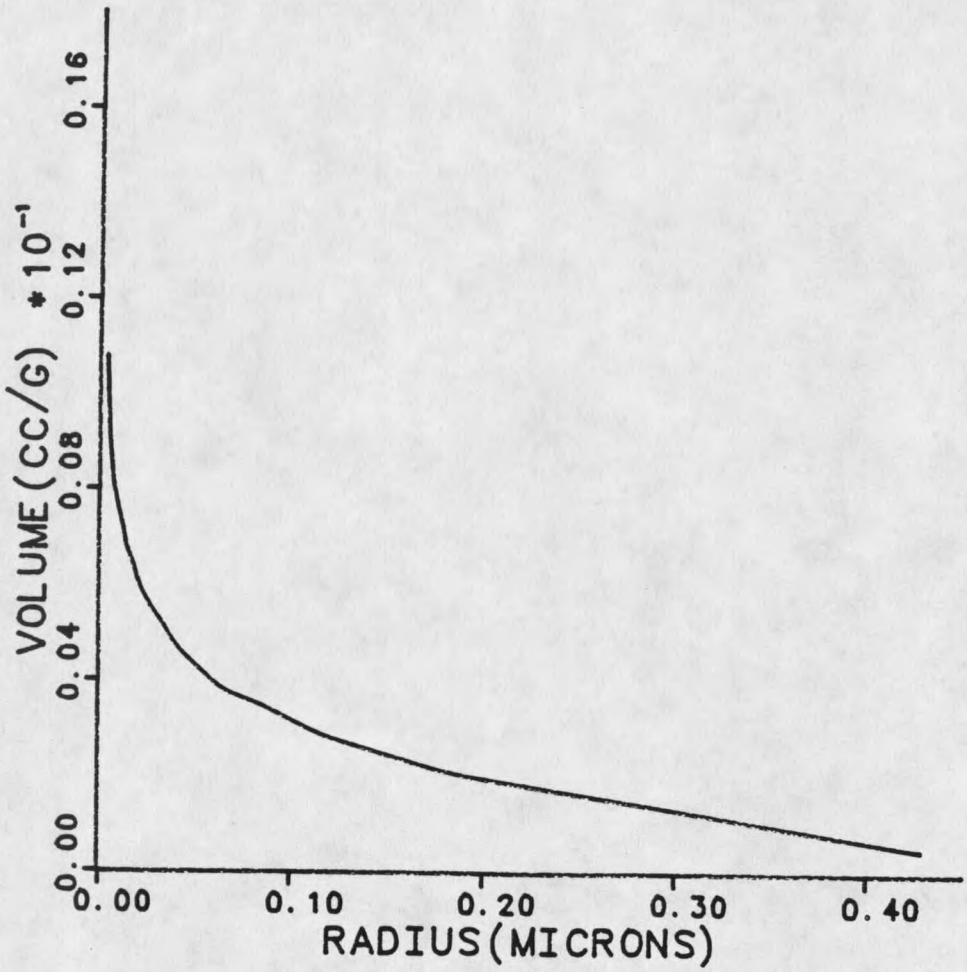

Figure 33. Radius versus volume of mercury for coal sample E83-24.

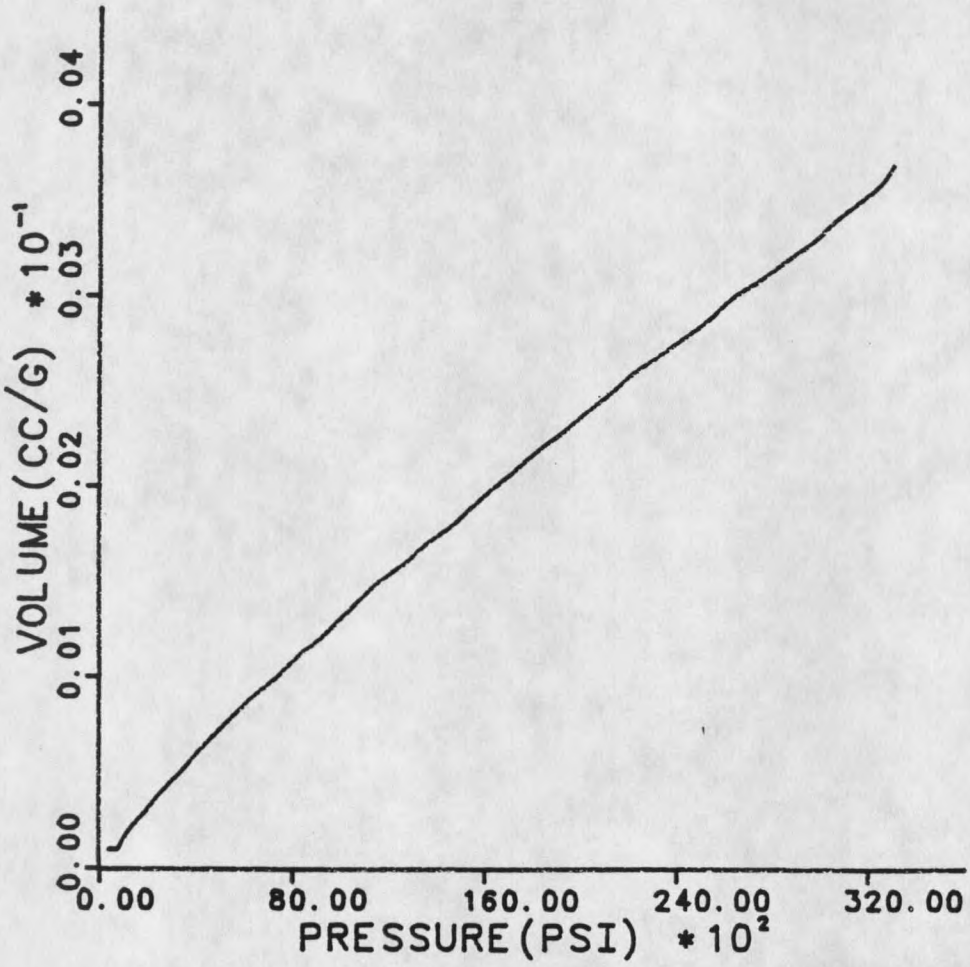

Figure 34. Pressure versus volume of mercury for coal sample E83-28.

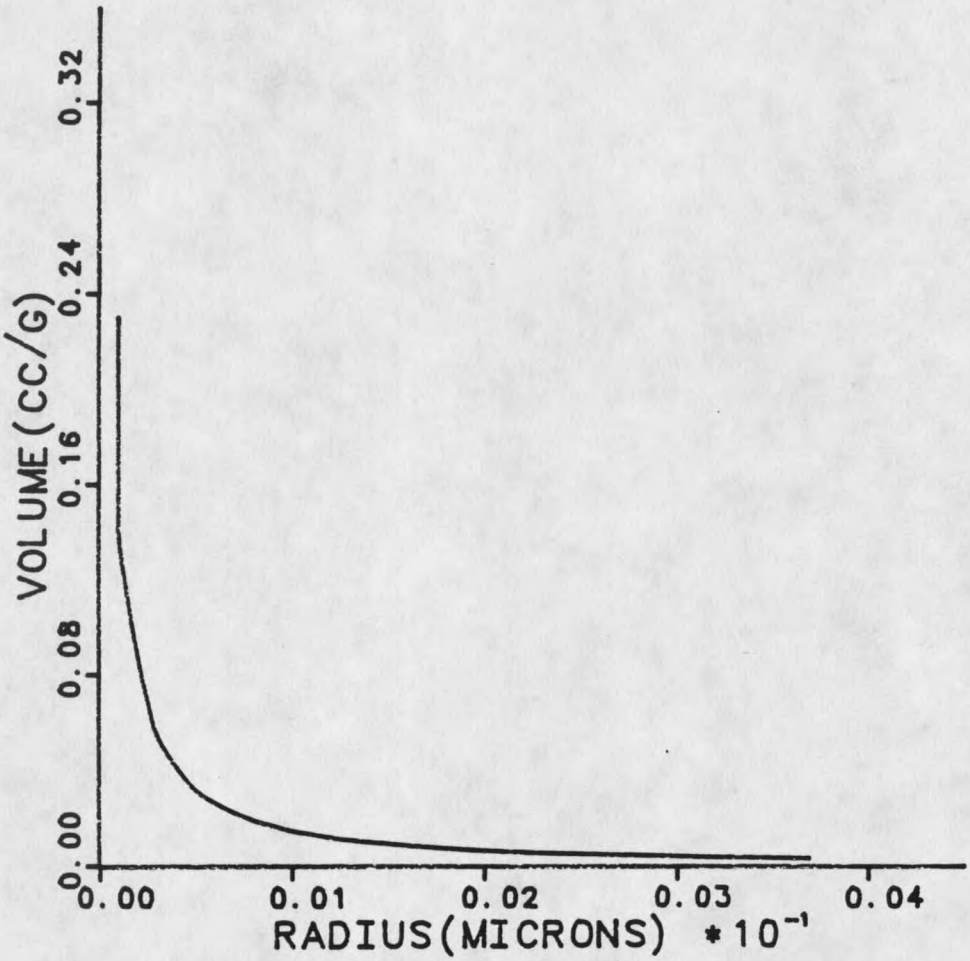

Figure 35. Radius versus volume of mercury for coal sample E83-28.

Helmer, Pamela E. P.
Estimation of methane content in Montana coals

DATE	ISSUED TO