Proceedings of the 1993 International Coalbed Methane Symposium
The University of Alabama/Tuscaloosa
May 17-21, 1993

COALBED METHANE INTERNATIONAL SYMPOSIUM
MAY 17-21, 1993
BIRMINGHAM, ALABAMA

9361

Effective Cleat Porosity & Cleat Geometry from Wood's Metal Porosimetry

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ABSTRACT

The cleat porosities of two coal cores from the San Juan Basin were investigated using several different techniques among several different laboratories. The coal cores were drilled along two orientations: perpendicular to the bedding planes, and parallel to the bedding planes (parallel to the face cleat). For these two coal cores, we found that the effective cleat porosity, defined as the percent volume of interconnected voids, depended on the orientation of the coal core. The orientationally-dependent porosity is a consequence of the direction of flow, chosen to be parallel to the axis of the core. The porosity was greater for the core drilled perpendicular to the bedding planes. Overall, we found that effective cleat porosities for these coal cores were much less than 1%. The core parallel to the bedding plane had a lower porosity but a higher permeability than the perpendicular core. This apparent paradox was explained using a Woods Metal injection technique. We found that 72% of the effective cleat porosity in the parallel core was contained in cleats with relatively large apertures greater than 2 microns. In the perpendicular core, only 36% of the effective cleat porosity was contained in apertures greater than 2 microns. The flow paths consisting of the largest apertures dominate and control the flow through the sample.

INTRODUCTION

Coal seams contain some of the richest known reserves of potentially recoverable natural gas. Evaluating the potential yield of gas from coal seam reservoirs requires an accurate determination of the effective cleat porosity of the coal. Absolute porosity of a porous material is defined as the percent of the bulk volume of the material occupied by voids,i.e., the ratio of void space to total bulk volume. Effective porosity, by contrast, is the percent of bulk volume occupied by interconnected pores. While porosity is an intrinsic property of a rock, effective cleat porosity will be an extrinsic property of the coal because the direction of flow will determine which pores are interconnected to the inlet and the outlet. Effective cleat porosity is important for determining the relative permeability of gas and brines that are often present in coalbeds. While the absolute porosity of coal ranges between 4.1% and 23.2% [1] the effective porosity from the network of cleats in coal is expected to be much lower [2]. Most measurements of coal porosity have been made on powdered or crushed samples which do not retain any of the features of the cleat network. The porosity of coal is usually determined using techniques such as gas adsorption (nitrogen, carbon dioxide), helium displacement, or mercury penetration. The values of porosity determined by these techniques vary because the measured porosity depends on several factors. These factors include: the particle size of the coal, the range of pore diameters in the coal particles, the molecular dimensions of the penetrant fluid, the degree of interaction between the penetrant fluid and the coal (i.e., swelling and surface effects), and the time allowed for fluid penetration. Discrimination between micro- and macro- porosity of the coal is possible by the proper choice of penetrant fluid (e.g., nitrogen versus mercury). However, because these methods are not generally applied to coal drill cores, not much is known about the porosity of the cleat network.

Gash's work [1, 2] on several coal cores from the San Juan Basin using the unsteady-state method (USM) has yielded effective cleat porosities ranging between 0.19% to 0.59% depending on the effective pressure the core was subjected to and on the orientation of the core relative to the bedding planes (Table 1). Standard techniques for porosity determination in conventional core analysis [4, 5] include techniques such as gravimetric measurements and gas expansion techniques. Traditional techniques, such as helium displacement, are unreliable when applied to coal drill cores because the experimental error is of the same order of magnitude (± 0.2%) as the values of effective cleat porosity. In addition, helium porosimetry methods yield the total porosity of the coal core because the helium can access all the voids in the coal core, not just the voids in the cleats.

Because the effective cleat porosity is used to determine the relative permeabilities of a coal sample to gas and brine, measurements of rock properties in coal require a high degree of precision and accuracy. This paper presents the results of a laboratory core exchange program to compare different cleat porosity and absolute permeability measurements on two coal cores using three different techniques: (1) Unsteady-state method (USM); (2) Modified porous plate method (PPM); and (3) Wood's metal method (WMM). The USM and PPM methods are commonly used and will only be briefly described. The Wood's metal method has only recently been applied to coal. The WMM experimental procedure and results will be discussed and compared with the results from the USM and PPM techniques.

SAMPLES

Two coal samples from Seam #1 of the in the Sundance Pit at the La Platta Coal Mine, in the San Juan Basin, in New Mexico (Figure 1) were used in the interlaboratory exchange program. The two samples were made from blocks of coal and had two different orientations relative to the bedding plane. Coal core AA was drilled perpendicular to the bedding planes; coal core BB was drilled parallel to the face cleat. The dimensions of the sample are listed in Table 3.

INTERLABORATORY CORE EXCHANGE PROGRAM

Two services laboratories were contracted to perform measurements of cleat porosity and absolute permeability on coal cores AA and BB as part of an interlaboratory core exchange program to compare different experimental techniques (Figure 2). The service laboratories will be referred to in this paper as Lab A and Lab B. Two techniques were used by Lab A. These were the unsteady-state method (USM) and the modified porous plate method (PPM). Lab B used only the unsteady-state method. In the modified porous plate method [6] the amount of brine produced from a coal sample is measured as a function of time for increments in helium injection pressure. This production data is used as input for a two-phase flow computer simulation to determine capillary pressure, relative permeability, and the cleat pore volume of the sample. In the unsteady state method, the coal core is saturated with brine that is subsequently displaced with helium. The volumes of helium and brine produced are recorded and used in a mathematical model to determine the relative permeability of the sample. Both Lab A and Lab B used helium as the displacing fluid.

The results from Lab A and Lab B are shown in Table 1 along with the data from Gash [3]. In Table 1, the cleat porosities for coal cores AA & BB are shown with the values of effective stress that the samples were subjected to during the measurement. Cleat porosity is dependent on the stress on the sample and on the pressure of the pore fluid. For core AA, the USM method used by both labs yielded approximately the same effective cleat porosity (0.22 % & 0.24%) for the same effective stress. For core BB, the effective stress used by the two labs differed, but a decrease in porosity was observed with increasing stress from 3.0 MPa (0.15%) to 6.7 MPa (0.11%). The PPM method used by Lab A yielded cleat porosities 1.2 to 3.9 times larger than the values of cleat porosity determined from the USM method, and show an increase in porosity with increasing stress. From the cleat porosity measurements performed by Lab A and Lab B, it is observed that the coal core oriented perpendicular to the bedding planes has a higher effective cleat porosity than the coal core oriented parallel to the face cleat.

Also shown in Table 1 are the absolute permeabilities (to water) of coal cores AA and BB measured by the two Labs. Lab B obtained an absolute permeability of 0.022 md for core AA. Lab A estimated an absolute permeability of 0.24 md for coal core AA. The value from Lab A had to be estimated because uncertainties in the data records and analysis of the water production curves showed that the permeability for core AA must be smaller than the permeability measured for core BB (0.13 md). Lab A reanalyzed the data and estimated an absolute permeability of 0.03 md for core AA. Lab A measured an absolute permeability of 0.13 md on core BB, which was confirmed by Lab B's value of 0.11 md. The importance of making more than one measurement of a coal core's properties is illustrated by the difference in permeability values measured by Lab A and Lab B on core AA.

From the service laboratory data on coal cores AA and BB, and the data from Gash [3] for cores AV & AFC, it is observed that the cores oriented perpendicular to the bedding plane have a higher cleat porosity and a lower absolute permeability than the cores oriented parallel to the face cleat. To understand why a high porosity sample would have a lower permeability, it is important to understand the geometry of the cleat network. Fluid flow through a permeable network of cleats is controlled by the geometry and the distribution of the void spaces within the cleat system. The cleats with the largest apertures dominate the flow. To gain a better understanding of the distribution of apertures in the cleats, the Wood's metal method (WMM) was applied to coal cores AA and BB using approximately the same effective confining pressure used by the service labs. A description of this method and the results follows.

WOOD'S METAL INJECTION TECHNIQUE

Background

Mercury porosimetry has been used to measure the void volume contained in coal pores (crushed samples) having apertures greater than 30 nanometers in diameter. Previous studies of coal porosity using mercury porosimetry [1, 7-11] provide a starting point and technical context for the study of coal cleat porosity (i.e., effective porosity) using Wood's metal porosimetry techniques. Mercury porosimetry [12] is based on the principle that the radius of a pore that is occupied by mercury is proportional to the ratio of the surface tension of the mercury to the pressure of the mercury. By measuring the pressure of the mercury and the volume of mercury injected, the pore radius distribution of pores in a material can be determined.

Wood's metal porosimetry was devised by Dullien [13] to examine pores in sandstones. Wood's metal is a Bismuth-based metal with a low melting point and a high surface tension (Table 2). Wood's metal porosimetry has been used to examine the pore structure of sandstones [13, 14], distribution of immiscible fluids in sandstone pores [15, 16], microcracks in granites, sandstones and carbonates as a function of stress [17], and fracture void geometry of fractures in granitic rock [18]. The technique is based on the principles of mercury porosimetry, that is, the injection pressure determines the size of the pore that the metal will penetrate. The main difference between mercury porosimetry and Wood's metal porosimetry is that in Wood's metal porosimetry one gains the added benefits of having a permanent cast of the void space geometry. The surface tension (Table 2) of molten Wood's metal is approximately the same as that of mercury.

An investigation of the porosity and pore structure of coal was performed using a Wood's metal infiltration technique [19] on crushed samples in the -20 mesh size range. While this investigation was able to examine the pores in coal, it did not yield information on the pore structure of fractures and cleats in coal. To analyze the void spaces in cleats, it is important to use a sample that has not been crushed or sieved. This paper presents the application of the Wood's metal injection technique on whole drill cores of coal.

Wood's Metal Injection Procedure

The research protocol for injecting a coal core begins with computerized X-ray tomography (CT) of the coal core before injecting the sample with Wood's metal. The pre-injection scan is used to determine the density variation in the coal samples and the presence of mineralized cleats. The CT analysis uses an X-ray beam width of 3 mm and an energy level of 120 keV. One pixel in the CT image represents a 2 mm by 2mm by 8 mm volume of the coal sample. Figure 3 contains pre-injection CT images of coal cores AA (Figure 3 a&b) and BB (Figure 3 c&d). For each core, two images are shown from different locations in the core. The CT images of coal core AA (Figure 3a&b) show no variation in density and no cleats are visible. For coal core BB, the light gray regions represent bedding planes that have a high density (Figure 3c&d). In addition, no cleats are visible and on image 3d, mineralization or a high density layer is apparent (dark, thick line).

After CT scanning, the coal sample is weighed, jacketed, and then placed in a hydrostatic pressure vessel where it is loaded to the desire confining pressure. Because the loss of moisture caused by drying [20] can lead to volumetric shrinkage of the coal matrix, a nitrogen back pressure is applied to reduce the amount of moisture lost during the heating of the sample for Wood's metal injection. A schematic of the experimental apparatus for Wood's metal injection is shown in Figure 4. The Wood's metal injection system is heated to a temperature between 95 °C and 100 °C and maintained in this range for an additional four hours to insure even heating. Wood's metal is injected into the coal sample using the pressure generator. A computerized data acquisition program is used to collect the confining pressure, Wood's metal pressure, nitrogen back pressure, and the temperature of the system throughout the entire injection process. After injection, the confining pressure is maintained while the system is cooled. After cooling, the coal specimen is removed and the sample is weighed again. The sample is CT-scanned to determine the location of the Wood's metal.

Results from Wood's Metal Method

Table 3 contains the results of the Wood's metal injection experiment performed on whole drill-core coal samples AA & BB. The effective cleat porosity of the sample is determined gravimetrically from the weight of the Wood's metal injected. The volume of voids filled with Wood's metal is equal to the weight of the injected metal (Table 3) divided by the density of Wood's metal (Table 2). The volume of Wood's metal in a coal specimen depends on the value of confining pressure and pore pressure at the time of solidification of the metal. This volume represents only the voids with apertures larger or equal to the minimum aperture filled by the injected Wood's metal (Table 3). The minimum aperture filled by Wood's metal can be estimated using the LaPlace equation for a cylindrical tube:

$$r = -2\gamma(\cos\theta)/P \qquad (1)$$

where r is the radius of the void (assumed to have a cylindrical geometry), γ is the surface tension of the Wood's metal, θ is the contact angle between the Wood's metal and coal in an air environment, and P is the Wood's metal pressure at solidification. The size of the aperture filled with solidified Wood's metal is inversely proportional to the pressure at solidification. The radius of the minimum aperture filled with Wood's metal was calculated from equation 1 using the surficial properties of Wood's metal listed in Table 2 and from the pressure measured during the experiment. For coal cores AA and BB, the pore pressure at solidification was 0.49 MPa and 0.44 MPa, respectively, which are similar in value compared with the 0.48 MPa pressure gradient used by the service labs. The minimum radius of the aperture filled with solidified Wood's metal for each sample is listed in Table 3.

The effective cleat porosity determined from this Wood's metal injection technique represents the porosity of the connected cleat network that has apertures greater than or equal to the minimum aperture filled with Wood's metal. The effective cleat porosity is calculated by dividing the volume of Wood's metal injected by the bulk volume of the coal sample. For coal samples AA and BB, the effective cleat porosity (for voids with apertures greater than 2 microns) is less than one tenth of one percent. The error of ±0.002 % is statistical error based on the measurement of the density of Wood's metal. The density of Wood's metal was measured on several pieces of Wood's metal before and after melting and was found to be $9.48 \pm 0.16\ \mathrm{g/m^3}$.

Figure 5 a-d shows the post-injection CT scans of coal core AA and BB at different locations in the coal core. The dark regions represent cleats filled with Wood's metal. Qualitatively, the cleat networks look significantly different for the cores, depending on whether they were drilled parallel or perpendicular to the bedding planes. For core BB, which was oriented parallel to the face cleat, rectilinear features are observed. It is also noted that flow through this sample occurs along bedding plane fractures as well as the cleats. The scans from two different locations in sample BB show that the cleats (or at least the void spaces within them) are not contiguous throughout the sample. The cleat structure in core AA which is oriented perpendicular to the bedding planes shows that the cleats are not planar but appear relatively contiguous.

CLEAT POROSITY & CLEAT GEOMETRY

The effective cleat porosity values determined from the WMM are lower than those determined from the USM and PPM methods under approximately the same conditions. This is not surprising because the penetrant fluid used to determine the cleat porosity (namely, Wood's metal compared with helium) is different and the pores that are accessed are controlled by properties of the penetrant fluid. The benefit of the WMM is that the pore size accessed can be controlled by the pressure of the Wood's metal. As mentioned earlier, the service labs and the data from Gash [2] show that coal cores from the LaPlatta mine that were oriented perpendicular to the bedding plane had a higher porosity but a lower permeability than coal cores oriented parallel to the face cleat. This seeming paradox can be explained from the WWM data. The ratio of the effective cleat porosity determined from the WMM to the effective cleat porosity determined from the USM method gives the fraction of the porosity composed of large apertures (in this case 2 microns and greater). Taking this ratio for cores AA and BB, we find that 76% of the total porosity of core BB is from voids with apertures greater than 2 microns, while we find that only 36% of the interconnected void volume in core AA is from voids with apertures greater than 2 microns. Though core AA has a higher porosity, this porosity is composed mainly of apertures less than 2 microns which support less flow.

The CT scans also show the difference in cleat geometry for coal cores AA and BB (Figure 5a-d). The Wood's metal-filled cleats in Figure 5 are represented by the black regions within the image. Coal core BB (Figure 5c&d) has planar fractures with larger apertures, while coal core AA (Figure 5a&b) has thinner fractures that are not planar. From the CT scans, the geometry of the flow network through these coal cores appear to be orientation dependent. In the future, cores AA and BB will be opened to examine the metal casts of the cleat network in the cores.

SUMMARY

Cleat porosity is one of the most important rock properties to measure on coal in order to make predictions of gas production. From the interlaboratory coal exchange program, it was determined that making one measurement of cleat porosity on a sample is not sufficient to insure an accurate value of cleat porosity. Also, it is important to understand the technique used to determine the porosity, the limitations of the technique, and the physical significance of the data. For two coal cores from the San Juan Basin in New Mexico, it was determined that the cleat porosity is less than 1%, and that the geometry of the interconnected voids in the cleats in these coal cores is dependent on the orientation of the coal core relative to the bedding planes. Understanding the geometry of the cleat network, and how it relates to the permeability and porosity of the sample, will aid in the development of models to predict and estimate potential gas production from coalbed reservoirs.

ACKNOWLEDGMENTS: This research was sponsored by the Gas Research Institute, Contract No. 5090-260-2003.

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Table 1. The effect of cleat orientation and effective confining pressure on cleat porosity and permeability of coal samples from the Sundance Pit, La Platta Coal Mine, San Juan County, N.M. determined using brine and helium for the penetrant fluids.

Flow Direction	Sample Number	Effective Confining Pressure† (MPa)	Effective Cleat Porosity (%)	Absolute Water Permeability (md)	Technique Used	Laboratory
Perpendicular to Bedding Planes	A V	0.79	0.53 - 0.59	0.8 - 0.04	USM	Amoco¥
	A V	4.6	0.28 - 0.32	0.007	USM	Amoco¥
	A A	2.3	0.22	0.022	USM	B
	A A	2.3	0.24	0.24£	USM	A
	A A	3.3	N.D.	0.031£	USM	A
	A A	4.5 - 4.6	0.45*	N.D.	PPM	A
	A A	4.5 - 4.6	0.45‡	N.D.	PPM	A
Parallel to Face Cleat	AFC	0.79	0.37 - 0.39	6.0 - 3.0	USM	Amoco¥
	AFC	4.6	0.19 - 0.27	1.7 - 0.6	USM	Amoco¥
	B B	3.0 - 3.1	0.15	0.13	USM	A
	B B	4.1	0.26*	N.D.	PPM	A
	B B	4.1	0.43‡	N.D.	PPM	A
	B B	6.7	0.11	0.12	USM	B
Parallel to Butt Cleat	ABC	0.79	0.5	4.8 - 1.6	USM	Amoco¥
	ABC	4.6	0.34 - 0.37	1.0 - 0.3	USM	Amoco¥

†Effective Confining Pressure = confining pressure minus mean pore pressure
**Measured Cleat Porosity ‡Computed Cleat Porosity £Estimated*
¥Gash et al. (1992) USM - Unsteady State Method PPM - Porous Plate Method N.D. = Not Determined

Table 2. Properties of Wood's Metal (Cerrosafe®)

Components:	
Bismuth	42.5 %
Lead	37.7 %
Tin	11.3 %
Cadmium	8.5 %
Melting Temperature Range	70°C - 88°C
Surface Tension (dynes/cm)	480
Average Contact Angle on Coal	130°
Density	9.4 g/cm^3
Young's Modulus	9.7 GPa

Table 3. Data from Wood's Metal Injection Experiments on Coal Samples AA and BB from Seam #1 in the Sundance Pit at the La Platta Coal Mine, New Mexico.

Sample Number	A A	B B
Dimensions (cm)		
Diameter	8.89	8.89
Length	4.41	11.18
Bulk Volume (cm^3)	273.81	693.99
Effective Pressure at Solidification (MPa)	4.4	5.1
Weight of Injected Wood's Metal (grams)	2.14	6.19
Radius of the Minimum Aperture Filled with Wood's Metal (μm)	1.25	1.4
Volume of Voids with Apertures ≥ Minimum Aperture Accessed (cm^3)	0.22	0.64
Effective Cleat Porosity (%)	0.082 ± 0.002	0.094 ± 0.002

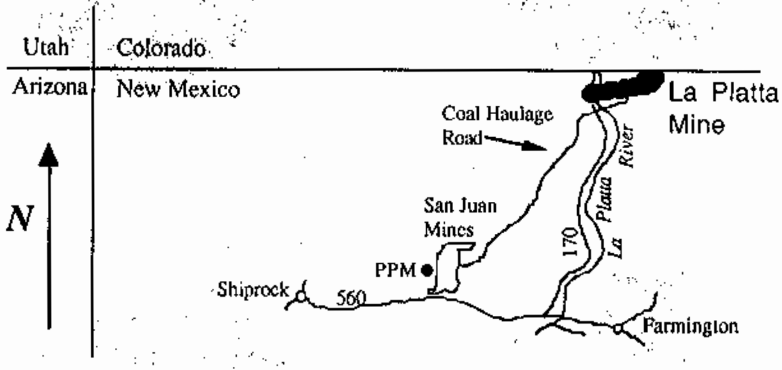

Figure 1. Sketch of the location of the La Platta Mine.

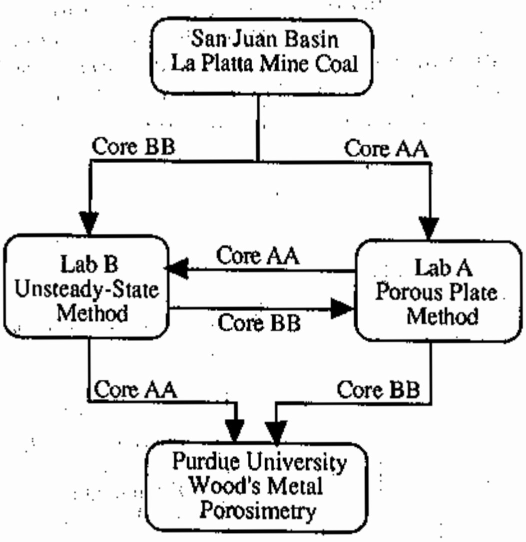

Figure 2. Flow chart of interlaboratory round-robin core exchange.

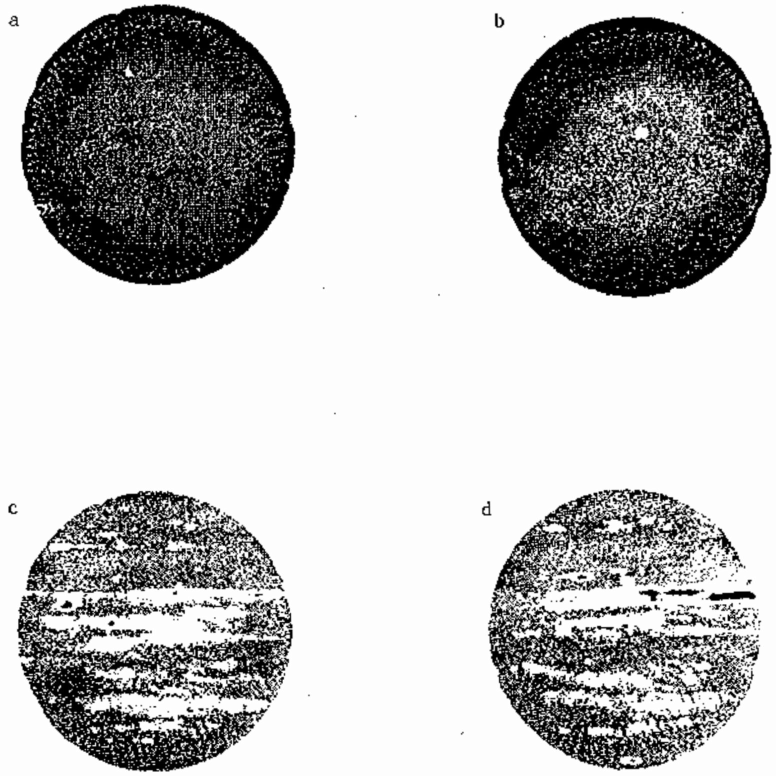

Figure 3. Pre-injection computerized X-ray tomography (CT) images of coal cores AA (3a&b) and BB (3c&d) are shown. Whitish regions represent high density bedding planes (3c&d), and blackish region within the core represent mineralization (3c & d). Coal core AA shows very little variation in density. Images a & b represent sections of coal core AA separated by 1.8 cm. For coal core BB, images c & d are separated by 4.4 cm along the length of the core.

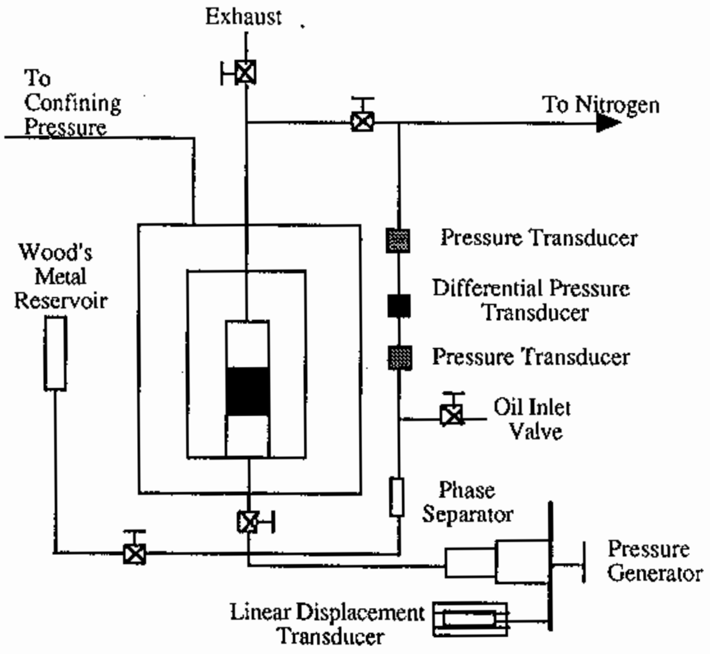

Figure 4. Schematic of Wood's metal injection system

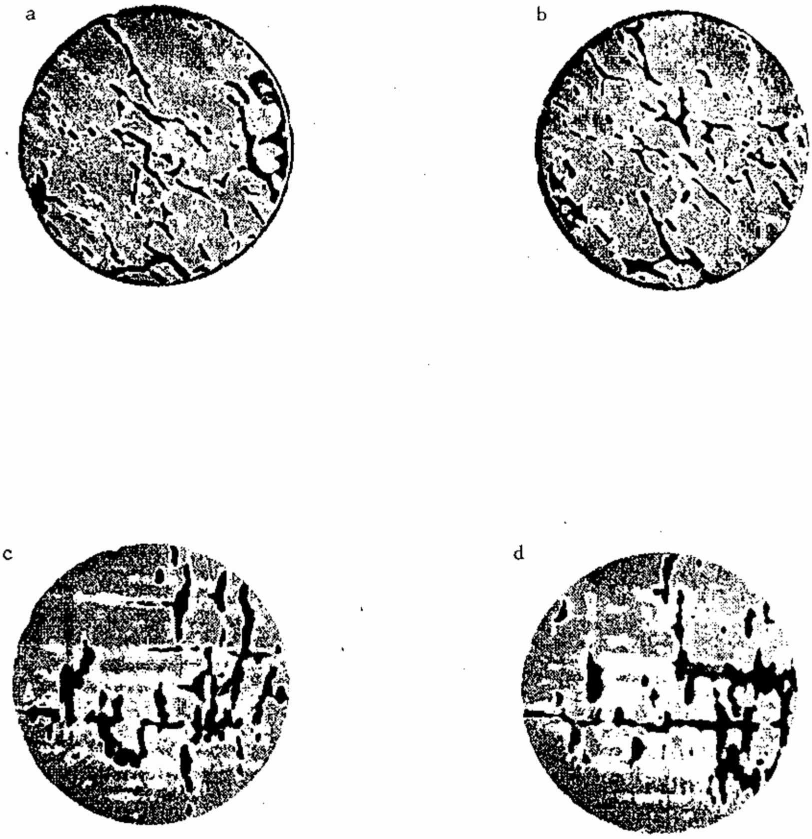

Figure 5. Post-injection computerized X-ray tomography (CT) images of coal cores AA (%a&b) and BB (5c&d) are shown. Black regions represent the presence of Wood's metal-filled cleats. Images a & b represent sections of coal core AA separated by 1.8 cm. For coal core BB, images c & d are separated by 4.4 cm along the length of the core.