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A study of permeability and porosity in pulverized coal

Samuel Lee Pace

To the Graduate Council:

I am submitting herewith a thesis written by Samuel Lee Pace entitled "A study of permeability and porosity in pulverized coal." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Mechanical Engineering.

Harold J. Schmidt, Major Professor

We have read this thesis and recommend its acceptance:

Lloyd Crawford, Roy Schulz

Accepted for the Council:
Carolyn R. Hodges

Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)

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We have read this thesis
and recommend its acceptance:

Accepted for the Council:

Associate Vice Chancellor
and Dean of The Graduate School

STATEMENT OF PERMISSION TO USE

Signature Samuel Lee Pace

Date May 22, 1991

A STUDY OF PERMEABILITY AND POROSITY IN PULVERIZED COAL

A Thesis

Presented for the

Master of Science

Degree

The University of Tennessee, Knoxville

Samuel Lee Pace, Jr.

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ABSTRACT

The purpose of this research was to experimentally investigate the relationship between porosity and permeability in pulverized coals. Permeability is defined as the ease with which a fluid passes through a porous medium. Permeability is a critical characteristic in the dense phase pneumatic transport of pulverized coal. The degree to which the transport gas can permeate through the porous mass of coal particles is important in order to maintain stable flow which is free of plugging. Porosity can be measured in both static and dynamic situations while permeability is measurable only in the static state and is dependent on particle size, size distribution and porosity.

The results of this experiment showed a strong relationship between porosity and permeability within a given coal particle size and the size distribution appeared to be very influential when comparing different coal preparations.

TABLE OF CONTENTS

1.0 INTRODUCTION 1

2.0 LITERATURE SEARCH AND BACKGROUND 5
2.1 Influential Properties 10
2.1.1 Porosity 10
2.1.2 Moisture 12
2.1.3 Coal Rank 15
2.1.4 Particle Size 17
2.1.5 Permeability 18
2.2 Darcy's Law 20
2.3 Permeability Measurement 25
2.4 Feasibility 27

3.0 EXPERIMENTAL SETUP 29
3.1 Procedure 38

4.0 RESULTS 46
4.1 Characteristic Variables 46
4.2 Feedstock Parameters 48
4.3 Porosity and Permeability Inputs 53
4.4 Calculated Quantities 64
4.5 Comparison and Correlation 66

5.0 CONCLUSIONS AND RECOMMENDATIONS 77

BIBLIOGRAPHY 80

VITA 84

LIST OF TABLES

TABLE PAGE

1. Results of Uniformity of Compaction Tests 42
2. Analysis of Selected Coals 47
3. Sieve Analysis of Eastern Coal 50
4. Sieve Analysis of Western Coal 55
5. Summary of Experimental Results 58

LIST OF FIGURES

FIGURE		PAGE
1.	Visual Observations of Various Flow Patterns	7
2.	Variation of Pressure Drop Along a Two-Phase Transport Line with Superficial Gas Velocity for Constant Total Mass Flow Rate	9
3.	Schematic Representation of Arching	13
4.	Flow Apparatus	23
5.	Experimental Apparatus	33
6.	Schematic of Water Displacement Flowmeter	36
7.	Cracks Due to Non-Settling Before Compaction	39
8.	Uniformity of Compaction Tests Using Flour Tracers	41
9.	Eastern Coal Size Distribution	51
10.	Size Distribution of Western Coal	54
11.	Size Distribution of Micronized Coal	56
12.	Eastern Coal Pressure Drop vs. Flowrate at Varying Compaction Pressures	60
13.	Western Coal Pressure Drop vs. Flowrate	62
14.	Micronized Coal Pressure Drop vs. Flowrate	63
15.	Eastern Coal Porosity vs. Mass Mean Diameter	67
16.	Eastern Coal Porosity vs. Characteristic Distribution Factor (CDF)	69
17.	Eastern Coal Permeability vs. Mass Mean Diameter	70

18. Eastern Coal Permeability vs. Characteristic Distribution Factor (CDF) 71

19. Eastern Coal Voidage vs. Permeability at 10 psi Pressure Drop 73

20. Western Coal Voidage vs. Permeability at 10 psi Pressure Drop 75

21. Micronized Coal Voidage vs. Permeability at 10 psi Pressure Drop.. .76

22. Summary of Eastern Coal Voidage vs. Permeability 78

LIST OF SYMBOLS

A	Area, in^2
CDF	Characteristic Distribution Factor, unitless
$\frac{dv}{dz}$	Fluid velocity gradient, ft/s
F_μ	Resistance Force, ft. lb_f/s^2
F_p	Buoyancy force, ft. lb_f/s^2
F_g	Gravitational force, ft. lb_f/s^2
k	Permeability, darcies
L	Length, inches
MMD	Mass Mean Diameter, microns
P	Pressure, lb/in^2
q	Volumetric flowrate, ml/min
r	Correlation coefficient, unitless
$\bar{x}$	Average value of flowrate, ml/min
V	Coefficient of variation, unitless

Greek Letters

ϕ	Porosity or voidage, unitless
μ	Viscosity, centipoise
ρ	Density, lb/ft^3
ρ_b	Bulk density, lb/ft^3
ρ_s	Single particle density, lb/ft^3
τ	Shear stress, lb/ft^2

1.0 INTRODUCTION

The transport of granular material, or bulk solids, is an important technology in many industrial applications and has, in many instances, been a source of plant inefficiency and considerable expense because of the lack of understanding of the physics involved in such transport. Significant expenses have been incurred in the design, construction, and operation of bulk solid transport systems, especially downtime expenses incurred when operation of transport equipment ceases. Gaseous and liquid feed stocks can be conveyed rather easily from one place to another with conventional means such as pumping. However, granular solids are more difficult to transport since they don't flow very well when subjected to pressure gradients in ducts and pipes. New technologies which require that granular solids be delivered in a more densely packed condition have generated the need for reliable, consistent delivery systems to convey the solids from storage tanks to the process locations. This is especially true in the case of pulverized coal which, on the one hand is an abundant fuel, but on the other hand has a solid form that results in handling difficulties which inhibit its wide spread use.

Processes like magnetohydrodynamics (MHD) combustors, pressurized fluidized-bed boilers, and entrained-flow-gasification require consistent coal delivery in a pressurized environment. Since the pressure of these devices is above atmospheric pressure, it becomes difficult and impractical to provide seals for mechanical feeders. To overcome this, pulverized coal is often suspended in a fluidic transport medium. One such provider of this type of delivery system is a coal-water slurry feed system. In this type of delivery system the coal is suspended in a carrier liquid, usually water. These systems are fairly reliable, but carry an energy penalty because of th energy needed to vaporize the water transport media. In fuel specific applications this can be overcome by using liquid fuels as the carrier medium. However, settling of the particles remains a problem. Dry feed systems, which use gas as the transport media and require smaller particles, thus have the potential of increased efficiency. This is especially true if a maximum coal-gas ratio or loading could be achieved. The carrier gas is much more easily stripped from the mixture than the liquid from the slurry. Almost all applications using pneumatic transport use dilute phase transport which is characterized by low values of solids loading, thus resulting in an essentially gas-like behavior in transport. The critical parameters for successful dilute phase flow are sufficient superficial gas velocity and turbulence levels which will hold the particles in aerodynamic suspension and insure reintrainment to maintain suspension. Another type of pneumatic transport is dense-phase transport, which is characterized by higher solids loading and lower gas velocities as compared to dilute phase transport. This type of transport does not depend on aerodynamic suspension of particles. Dense phase transport has several advantages over dilute phase transport. These include minimium carrier gas usage, smaller transport lines, lower abrasive erosional effects, the ability to convey fragile materials with less degradation, and the ability to convey over longer distances. Regretfully, there is very little design data available to aid in the proper design and control of a dense phase feed system. Much of the information available comes from the U.S. Bureau of Mines and Rockwell International who are involved in the production of Synthetic Natural Gas (Zenz and Othmer, 1960). Their information highlights the need to investigate all parameters involved in dense phase pneumatic conveying. General Mills and others have proprietary data on dense phase transport. Other users of dense phase transport include the Coal Fired Flow Facility (CFFF) at The University of Tennessee Space Institute (UTSI). At this facility dense phase transport is used to feed a coal fired combustor for magnetohydrodynamic (MHD) energy conversion. This system, although successful and reliable, has been and continues to be operated and improved on a trial and error basis. Another application of dense phase transport is the Advanced Combustor Project, also at UTSI, in which a commercial oil fired boiler was modified to fire micronized coal (Foote , 1989). Again, the development and operation of this feed system has been characterized by trial and error. The development of the latter feed system widely illustrated the profound impact a single parameter, the particle size, has on successful operation. These projects point out the need for a broad fundamental understanding of dense phase coal flow and the effect various parameters have on it. One of these factors which appears to have a strong influence on dense phase pneumatic transport of coal is the dynamic permeability.

In this investigation it will be attempted to correlate porosity and permeability in the static state with the longer range goal of extending this to the dynamic state which is of more interest in actual feed systems. This static correlation was done by investigating the influential parameters, isolating the variables of interest, designing and performing a battery of experiments, and correlating and discussing the acquired results.

In Section 2 the available literature is surveyed to summarize dense phase pneumatic transport of coal, along with the parameter which affects its usage and performance. For key parameters emphasized in Section 2, the experimental apparatus and procedures employed to perform this investigation through a battery of experiments are discussed in Section 3. In Section 4 the results of these experiments will be presented. Finally, in Section 5, conclusions are drawn from the results and recommendations made for improvements and further work.

2.0 LITERATURE SEARCH AND BACKGROUND

Dense phase transport, which is inherently more simple than its dilute phase pneumatic transport counterpart, has not been studied or widely applied in industry. As a consequence of this lack of use a general lack of understanding of the physical phenomena associated with dense phase flow exists. This hinders the wider usage and potential advantages offered by dense phase coal flow in combustion environments.

At present, several applications of dense phase flow are currently taking place. One of these is at UTSI where MHD energy conversion is being done. In this process, the MHD working plasma comes from the combustion of pulverized coal and an oxygen enriched oxidizer at an elevated pressure. In this system the MHD combustor which operates at approximately 6 atm is fed pulverized coal in a dense-phase feed line. The pressure requirement, along with the requirement to maintain the carrier gas volume at a level which does not substantially reduce the combustion temperature and thus affect plasma electrical conductivity, have required the use of a dense phase system.

Other current applications of dense phase flow include fluidized bed boilers and the delivery of ground peat in gasification experiments. With today's concern for energy the increased utilization of coal becomes very important. This necessitates that large volumes of solid material must be moved during the many stages of the energy conversion process. As stated by Klinzing , "To a great extent one must still rely on some of this empiricism... questions still remain concerning the design of the dense choked-phase regions of flow and horizontal flow having saltation effects. These important regions of flow are finding increased use in industry" (Klinzing, 1981).

When the flow pattern of a solid being conveyed pneumatically in a tube or pipe is observed, the flow patterns are rather complex (Figure 1). At low solid to gas ratios the moving solids particles are distributed fairly evenly in the pipe. This type of flow, termed homogeneous flow, is characterized by radial and axial density variations, which are insignificant in that groups or clusters of particles cannot be identified. As the solid-gas ratio increases, some particles begin to settle to the bottom of the pipe and slide over other particles forming dunes. As the solid-gas ratio increases further, the segregation reaches a limiting point where the solids begin to move from dune to dune. Slug flow, which is the intermittent flow of gas and solids in alternating slugs, results from even higher solid gas ratios. Eventually, as the solid loading increases, the particles fill up much of the cross-sectional area of the transport pipe. In this flow regime, the gas and solid particles flow in the form of ripple, with the majority of the solid staying stationary. Eventually, the maximum loading is achieved and the pipe becomes plugged (Sprause and Schuman, 1983). Some factors which affect this flow are the solid-gas ratio, the Reynolds number of the flow and specific properties of the solid. The two limiting types of flow are dilute-phase and dense phase, which are the general regions at the ends of the sequence illustrated in Figure 1. The difference in the two can be explained in vertical transport using the following explanation. If a solid is transported using

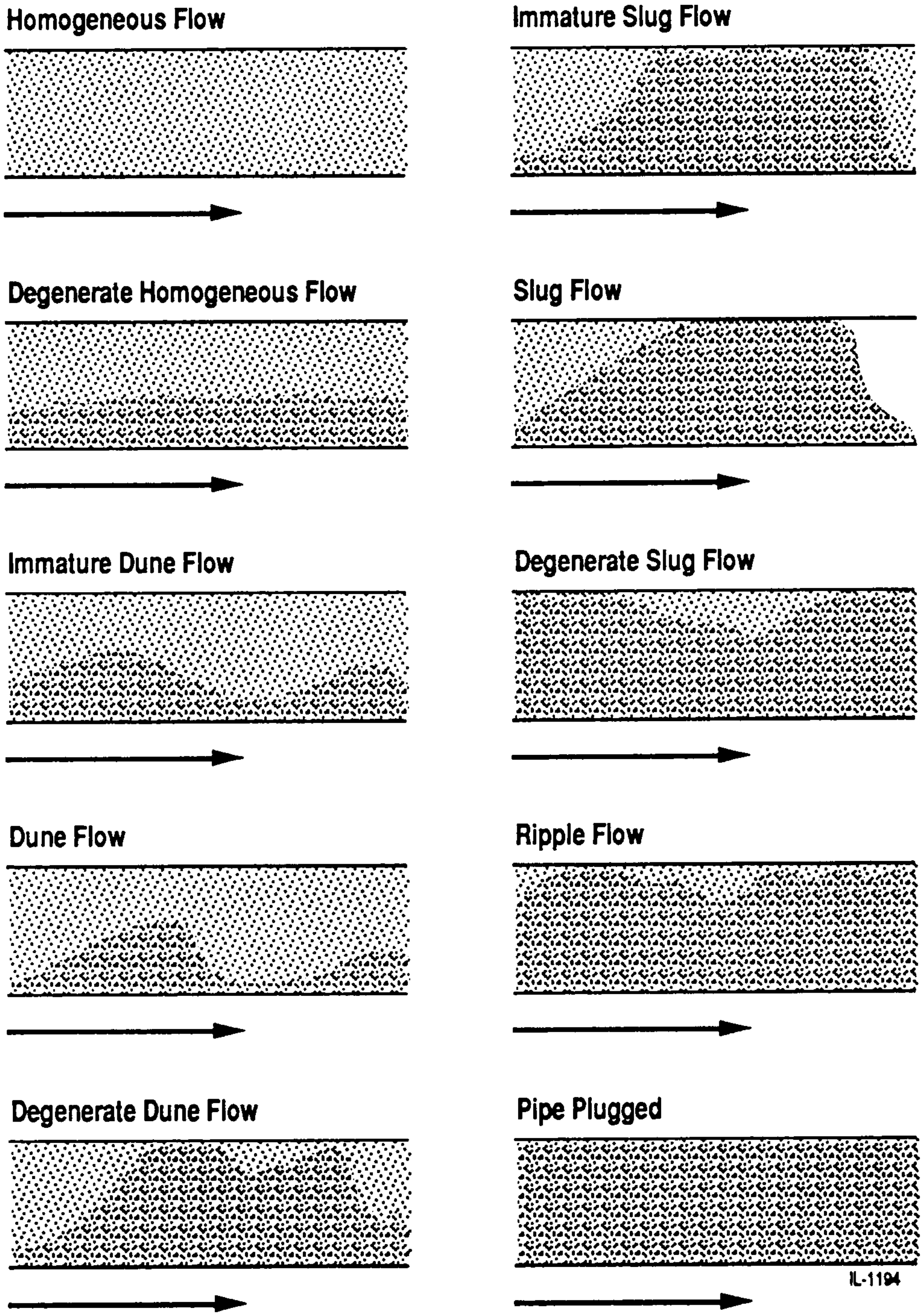

Figure 1. Visual Observations of Various
Flow Patterns (Marchello and Gomezplata, 1978)

a large amount of gas, a certain pressure drop is found to exist. If the gas velocity is reduced while the rate of solids transport is maintained, the pressure drop will decrease. As seen in Figure 2, there is a certain velocity of the gas at which a minimum pressure drop is experienced. This point of minimum pressure drop is used as the demarcation between dilute and dense phase transport. Gas velocities lower than the point which produces minimum pressure drop will produce higher pressure drops, and choked-flow or slugging occurs. This is the dense phase region. The region of higher gas velocities than the choking point is the region of dilute phase transfer. In horizontal flow, a similar situation exists. In the horizontal case, the pressure drop changes more abruptly. The pressure drop is due to settling or saltation at the bottom of the pipe which creates a pipe of decreased cross sectional area. Once again, like the vertical case, the region of lower velocity causes an increased pressure drop in the dense phase region, while the region of higher velocity also causes an increased pressure drop and is the dilute-phase region. It is very important here to remember that the solid transport rate is constant in this description. Thus the solid to gas ratio must be changing to accommodate these velocity changes while maintaining the overall rate. Therefore, in the dilute region or higher gas velocity, the solid gas ratio must be less than that of the dense phase region which has a lower velocity. Even though this demarcation between dilute and dense phase flow appears straightforward there is a variety of flow regimes within each of these general descriptions.

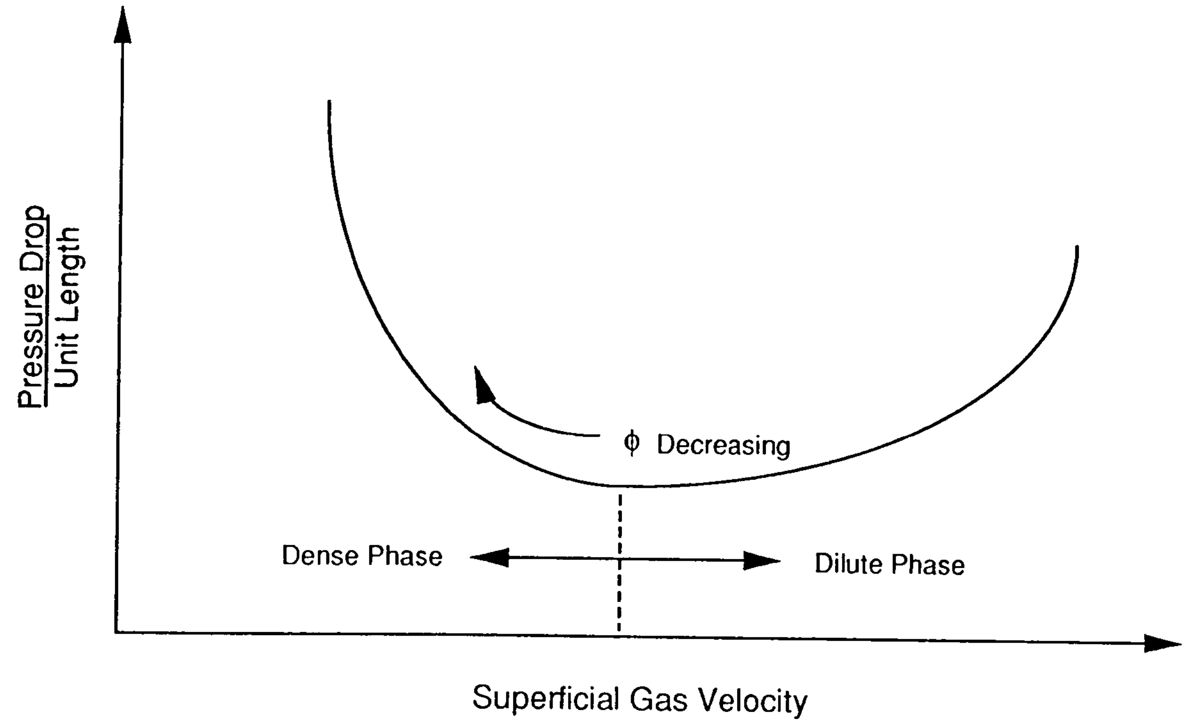

Figure 2. Variation of Pressure Drop Along a Two-Phase Transport Line with Superficial Gas Velocity for Constant Total Mass Flow Rate (Klinzing, 1981)

2.1 Influential Properties

Many factors or properties influence the qualitative and quantitative behavior of the transport of coal in dense phase pneumatic transport systems. These physical parameters hold the key to better understanding and, ultimately, the utilization of dense-phase coal transport. These parameters include: porosity, moisture, coal rank, particle size, shape, size distribution, cohesion, and permeability acting individually and in unison. This research program examines these factors both as primary variables and contributing variables, to begin to formulate a solution to the complex equation of dense-phase coal flow, although a complete and verified formulation is beyond the scope of the present investigation.

2.1.1 Porosity

For simplicity and practicality, the solid to gas ratio is defined as the voidage or void fraction, also called the porosity of the bulk transport. The voidage is defined as the fraction of the bulk volume of the material occupied by voids. This is the same as the carrier gas volume per unit total volume and can be represented by the following equation

$$\phi = \frac{\text{Gas Volume}}{\text{Gas Volume} + \text{Coal Volume}} \tag{1}$$

The voidage for gas flow alone equals one and approaches zero as the solid loading in the flow increases (Schmidt and Chapman, 1990). There are two classes of voidage or porosity, absolute and effective porosity. The absolute porosity takes into account the possible internal pores of a substance. It does not require that a pore be a possible communicable path of gas flow (Lowell, 1975). On the other hand, effective porosity requires that the pores be interconnected or a possible path of gas flow. Some natural rocks, like lava and igneous rocks, have a high total porosity but hardly any effective porosity. Effective porosity can be an indicator of permeability but not a measure of it. The void fraction, or porosity, depends upon the size distribution and the theoretical solid density of the solid, or coal in this case.

The particle size and size distribution are two predominate characteristics which influence variations in voidage. If the distribution of particle sizes is sufficiently wide, the smaller particles will be able to fit into the empty locations within the matrix of larger particles. The larger particles will always create void space, due to arching effects, thus there is always room to be filled by the smaller particles. This results in a more tightly-packed matrix and reduces the void volume, or voidage.

The other material property influencing voidage is particle size. Particle size is described in terms of the geometric or arithmetic average diameter. Smaller particles have lower mass-to-surface area ratio. This leads to less settling and causes the amount of bridging or arching to increase which results in higher voidages. In addition, particle size and size distribution are not wholly independent for, as particle size is diminished, the size distribution becomes more compressed.

Arching, the phenomena responsible for the effects of particle size and size distribution on voidage, can be described with the following illustration and example. If we use spheres to represent the individual particles, the two cases of arching and no arching are illustrated in Figure 3. In the no arching case, it can be shown that the minimum stress is achieved in the contact stress and base stress. In the arching case, maximum contact stress and redistribution of base stresses is achieved.

The porosity for a given material is the deviation of the apparent bulk weight of a mass of its particles from relative weight of one of its particles. The greater this deviation, the larger the porosity. Cohesive nonflow materials like zinc oxide, iron oxide, calcium hydroxide and titanium dioxide have porosities greater than 80%, while more free-flowing materials, such as sand, have a porosity of 45% (Marchello and Gomezplata, 1978). Usually, free flowing materials have a porosity between 35 and 50%.

2.1.2 Moisture

Another basic material property which affects flow characteristic is moisture content of the material. The presence of moisture can be an advantage or a disadvantage. Moisture increases the cohesion of a material by the increase in capillary force, between particles, which causes a decrease

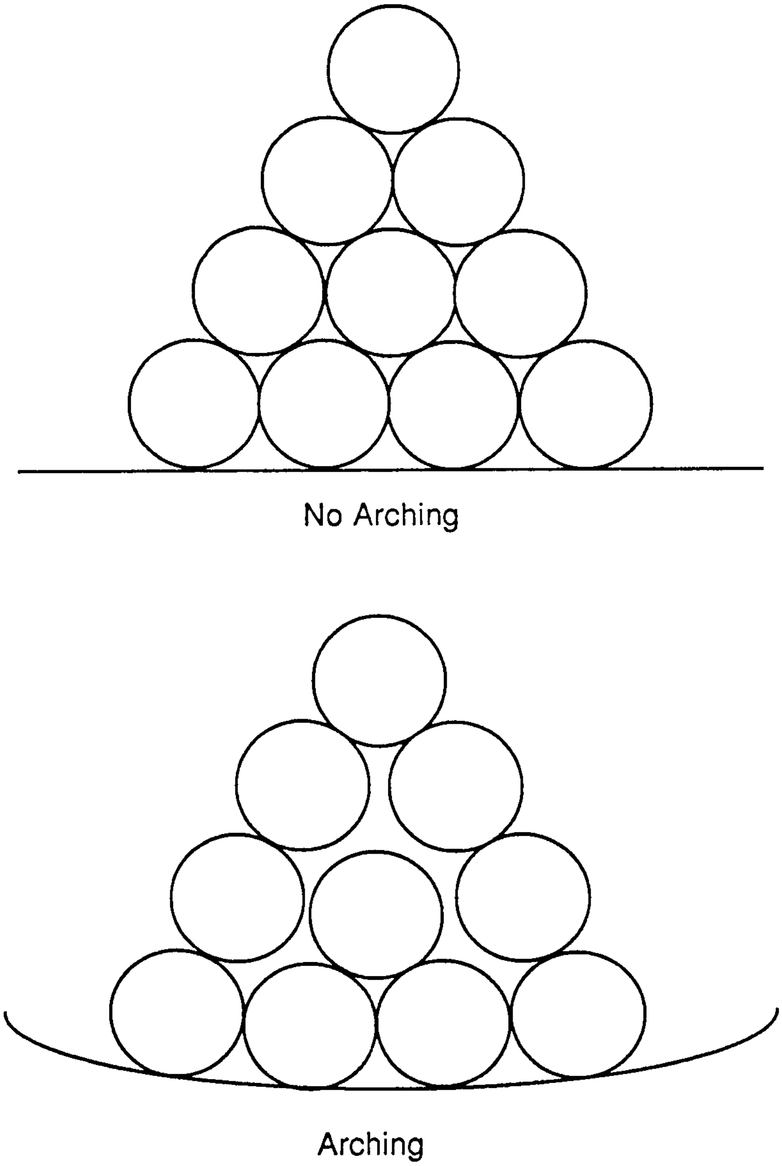

Figure 3. Schematic Representation of Arching (Hawk, n.d.)

in the material's flowability. On the other hand, excessive amounts of moisture can tend to lubricate the particles lessening their resistance to shear forces. This tends to improve the flow characteristic of the material.

There are several ways to classify the moisture associated with coal. Total moisture is determined by removal of all moisture from the particles surface and pores using a standard temperature condition. The moisture which, by nature, is found in the actual coal seam deposit, including water held in pores and in chemically bound hydrates is called the inherent moisture. Free moisture is the difference between total moisture and inherent moisture. Free moisture is also known as surface moisture when the solid material is coal.

The capillary forces which can cause cohesion among particles and impede flow are generated by liquid bridges between particles. There are three different states of liquid bonding which have been found. These are based upon the material's saturation with moisture. The first of these states occurs at low saturation levels. In low saturation, or pendular state, liquid bridges are created between particles while no void spaces located between the particles are totally filled. As the saturation level increases, the funicular state of liquid bonding is achieved. In this state some of the void spaces become filled.

When all of the void spaces are filled completely, the capillary state is achieved. At lower levels of saturation in the pendular state, the capillary pressure is much greater than that of the particulate which is completely saturated at the capillary state. This difference in capillary pressure can be attributed to the difference in the radius of the water meniscus in between particles. In the low saturation condition, the meniscus has a very small radius contrasted by the large radius with reduced capillary action seen at high levels of saturation. The capillary pressures that accompany the draining of the pore spaces are greater than the capillary pressures which are created as the pores are filled. In coal, the nature of the coal's surface rather than its surface areas determines its ability to absorb water. Lower rank coals with more inorganic mineral matter tend to absorb more water (Arnold, 1990).

It appears from several experiments conducted by others that the moisture increases the strength up to a limiting value, beyond which the strength begins to reduce again. The shear strength of moist coal has been found to be higher than the strength of dry coal (Hogg, 1986). Hogg also found in this study that as moisture increased so did cohesiveness. Johanson summarized the effect on moisture by generalizing that the effect of an increase in moisture content will increase the compression strength of the material as long as saturation is not approached, thus hampering its flowability up to this point (Johanson, 1978).

2.1.3 Coal Rank

Coal rank also is suspected to have an influence on coal flow. Coal is ranked to categorize the specific properties of the material. The lowest ranked coals are the lignite, with anthracite being the highest rank. Coals are ranked using three physical and chemical properties. These properties are the content of the fixed carbon, volatile matter and the higher heating value. For anthracite, the highest ranked coal, the fixed carbon lower limit is 86 percent and the volatile matter upper limit is 14 percent. Anthracites have no specific gross caloric value determined. Bituminous coals have fixed carbon upper limit of 86 percent. The various grades of bituminous coal are distinguished from one another by their fixed carbon content. The lower limit value for gross calorific content for bituminous coal is 11,500 British Thermal Unit (BTU) per pound. The third general classification of coals are the subbituminous coals. Subbituminous coals have an upper limit of 11,500 BTU per pound and a lower of 8,300 BTU per pound for the gross calorific value. Some authors have suggested that flow properties improve with the higher rank of coal due to its fracturability and porous nature. One reason for this may be that higher-ranked coal are less susceptible to degradation during storage and handling. A more probable reason for the better performance of higher ranked coals are their resistance to water absorption. Higher rank coals have a smaller ratio of pore volume to particle volume, smaller pore size distributions, and smaller specific area than lower ranked coals. This smaller pore space results in a lowered affinity for water absorption. Also, higher rank coals have smaller amounts of inorganic mineral matter such as, clay, quartz, calcite or pyrite, which in increasing proportion tend to aid its water absorption ability. The increased flowability of higher rank coal, through lower nondegradation and absorptivity, can be traced back to the previously mentioned issue of pore size or porosity.

2.1.4 Particle Size

Particle size which has been shown to affect porosity actually directly affects the flowability of bulk solids such as coal. It has been for the most part found to be true that the finer the particles the greater the problems with flow ability in dense phase transport. This becomes of increasing importance as the use of smaller particles become more common. This is especially true of coal which requires deep cleaning to remove impurities, which by the nature of the cleaning process require smaller particles. As a result of the particle being smaller the surface area to mass ratio is significantly increased. This increases the role of the surface chemistry in the flow process. As the concentration of smaller particles increase the cohesion among particles also increases. This cohesion causes arches which tend to prevent the flow of material. It also has been shown that the tensile strength of a bulk solid is very strongly dependent on particle size (Furley, 1967). They found that as the particle size decreases the strength of the bulk material increases. From strength and cohesion increases, associated with diminishing particle size, it can be concluded that the particle size strongly affects the structure of the powder while the increase in surface or contact areas and the associated forces influence the strength of the structure. Another effect of the surface area to mass increase in a smaller particle is an increased ability to absorb moisture. The effects of moisture on coal flow have been shown to be important.

2.1.5 Permeability

Permeability appears to be a very important parameter when trying to characterize coal flow. As discussed with porosity, particle size, particle size distribution and even moisture, the pore structure of the material is greatly affected. Permeability is the parameter which best describes the rate of fluid movement through this porous structure. Collins states that , "permeability is that property of a porous material which characterize the ease with which a fluid may be made to flow through the material by an applied pressure gradient. Permeability is the fluid conductivity of the porous material" (Collins, 1961). This flow through a porous material is a function of the pore space, the viscosity of the flowing gas and dimensional factors such as the area of the particle bed and the powder or solids specific surface. The dependence of permeability on the specific surface of the powder, which can be estimated from knowing the flow rate of the fluid along with other influential factors, leads to the usage of permeability to estimate mean particle size. One of the reasons for this important relationship is, as we shall later see, that the equipment for measuring permeability is rather simple. The use of permeability as a valuable parameter in characterizing fluid flow conductivity in porous materials was demonstrated first by Darcy in 1856. From his work the empirical equation which describes permeability in terms of measurable quantities is called "Darcy's Law". It is written as follows

$$k = \frac{q\mu}{A\,(\Delta P/L)} \quad (2)$$

It is applicable to the flow of an incompressible fluid through a length of porous material L in the flow direction with a cross-section A. The parameter q is the volumetric flow rate of the fluid while μ and ΔP are the viscosity of the fluid and the pressure difference across the porous material respectively. Knowing these measurable quantities, "k", the permeability can be determined. From dimensional analysis of the above equation it is shown that "k" has units of length squared and this is a rough measure of mean square pore diameter of the material. It is also assumed in this relationship that the porous material is isotropic and does not have a directional dependency in make up or structure. This is not a valid assumption for fibrous materials such as wood or sedimentary rock but for pulverized coal this seems to be a valid assumption. The unit used most commonly to express permeability is the Darcy which is defined as a fluid flow rate of 1 cubic centimeter per second of a fluid having 1 centipoise viscosity through a cube having 1 cm sides under a pressured difference of 1 atmosphere

$$1 \text{ Darcy} = \frac{1\ (\text{cm}^3/\text{sec}) \cdot 1\ (\text{cp})}{1\ (\text{cm}^2) \cdot (\text{atm/cm})} \quad (3)$$

It should be noted here that permeability as defined by Darcy's Law is a macroscopic property of the material. Thus the sample of porous material used must be significantly large to contain many pores. It also seems important to note that, as previously discussed, that permeability is determined by the geometry of the porous material in a roughly statistical manner. This points to the already mentioned importance of particle size distribution. From practical application in dense phase conveying applications the permeability seems to be one, if not the key factor, in helping understand coal flowability problems. This belief can best be illustrated by the fact that upon pluggage of a coal line both the gas and coal flow cease which points to a condition of low permeability with the coal and fluid behaving as a unit. That is, the slip velocity is low. Another observation is that unlike fluid flow or dilute phase flow a finite pressure gradient can be sustained in a dense phase transport line without motion.

2.2 Darcy's Law

Before going on to the physical measurement of permeability and the application of its measurement, a closer look at the model which is used to justify Darcy's Law is merited. For laminar flow, which is assumed in Darcy's Law, and can be shown by calculating the Reynolds number, the fluid flow follows a set of fixed streamlines. An element of fluid which is following the path of another element must follow this preceding element throughout its course. In contrast, turbulent flow has only a partial correlation of particle paths. The viscosity used in Darcy's law, μ, is the measure of internal friction associated with laminar flow. Shear exists between laminar streamlines having different velocities. As expected, at the surface of the solid the fluid has a velocity of zero. In an ideal viscous fluid, the fluid will adhere or stick to the solid surface.

Since the fluid is viscous and sticks to the surface a drag force is exerted on the solid and the fluid tends to drag the solid along with it. If however the solid is held in a fixed position, as in the experiments which will be described below, a force equal and opposite the fluid movement is exerted on the fluid by the solid. This force of viscous resistance is equal and opposite to the drag force on the solid in the moving solid case. From Newton's equation the shear stress existing between fluid and solid is given by

$$\tau = \mu\left(\frac{dv}{dz}\right) \tag{4}$$

where μ is the fluid viscosity, and $\frac{dv}{dz}$ is the fluid velocity gradient of the surface. From Newton's second law of motion, force must be applied to a fluid to change its direction or velocity. Since the fluid in this case is flowing through a very non-linear flow path, the force which cause these changes in a fluid element's velocity and direction, varies from point to point throughout the flow path. Since the number of flow paths in a large sample of porous material is large and assumed random in character it can be assumed that the random changes in velocity and direction for any fluid element are uniformly distributed. It also can be assumed that the variations in magnitude of velocity are uniformly distributed and have a mean of zero. Thus using this concept of a macroscopic volume (macroscopic property) the lateral forces that coincide with random changes in velocity for steady laminar flow can be expected to be zero. However the inertial force, along the direction of flow will not average to zero but will only be negligible for low flow rates.

In terms of the macroscopic view the only force exerted on the fluid by the solid is the viscous resistance to flow. In steady laminar flow this force has to be in total equilibrium with external and body forces, on the fluid element. To visualize the physical concept of the above description consider a physical set-up as shown below (Figure 4). In this apparatus we have a sample of porous material of length L and cross-section A. The sample is fixed into position in the apparatus so that no fluid can escape without passing through the solid. When the flow of the fluid is upward through the sample a viscous resistance force is directed opposing the flow. For laminar flow the relative velocity distribution within the sample is independent of the velocity's magnitude. Thus velocity and $\frac{dv}{dz}$ must be everywhere proportional to q/A where q equal to volume flow rate. For a given sample of given particle size the total surface is proportional to the bulk volume of the material as fixed in the apparatus (AL). Therefore, the viscous resistance or drag on the fluid can be written as

$$F_\mu = B\mu qL \tag{5}$$

where B is a constant with units of reciprocal length squared and is determined by pore geometry, just like permeability is. This force F_μ is opposite in direction to flow. The external force acting upon the fluid which is contained within the porous sample can be expressed using the two pressures located at the ends of the sample P_a and P_b. The pore area is a function of the porosity ϕ and the cross-sectional area A therefore the net upward force on the fluid due to this

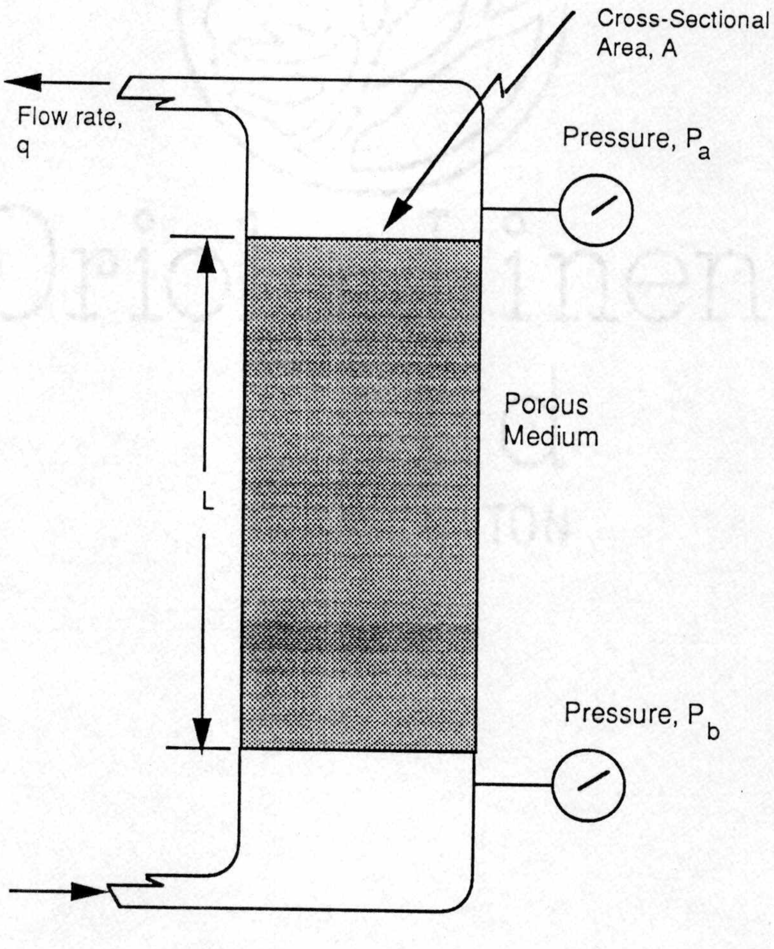

Figure 4. Flow Apparatus (Collins, 1961)

pressure difference is

$$F_p = (P_b - P_a)\, \phi\, A. \tag{6}$$

The body force acting on the fluid is due to the weight of the fluid in the sample area and is a downward force expressed as

$$F_g = \rho\, (\phi A L)\, g \tag{7}$$

with ρ being the fluid's mass density and g being the acceleration of gravity. Since it is a steady flow situation in which we are interested the forces must be in equilibrium. F_μ, F_p, F_g must balance. Writing a force balance as follows

$$B\mu q L + \rho(\phi A L) g = (P_b - P_a)\, \phi A \tag{8}$$

rearranging and

$$F_\mu + F_g = F_g \quad \text{or} \tag{9}$$

substituting $\phi/B = k$ we arrive at Darcys Law for vertical flow

$$q = \frac{kA}{\mu L}\left((P_a - P_b) + \rho g L\right) \tag{10}$$

The constant k is characteristic property of the porous medium. The parameter k is referred to as the permeability for a porous substance as defined by Darcy's law. Actually Darcy's law was developed empirically with the above explanation serving as a guide to the physical principles behind and justifying its use. For a more rigorous mathematical proof of Darcy's law two different approaches are known to exist. One employs the usage of volume averaging the Stokes equation and has been done by Hubbert in 1956 and others since (Larson, 1981). The other employs the use of general Stokes equations without using the volume averaging approach (Larson, 1981). If one considers the effect of compressibility in gases, whole new complex equations can be developed. For the purpose of the present experiment the gas compression effect will be assumed to be negligible , due to the low Mach number of less than 3. A Mach number of less than 3 is the commonly accepted limit for air at standard conditions to be considered incompressible (White, 1974).

2.3 Permeability Measurement

As described in the physical example of Darcy's Law the static measurement of permeability is rather simple (Cadle, 1962). By controlling the containment of gas flow through the sample and taking precaution to contain the sample itself accurate measurements are attainable.

In the dynamic state the shear strength and the handleability of micronized coal appear to be very dependent on the porous materials ability to equate or communicate pressure change, throughout the media. Therefore, the permeability becomes a very important factor in determining how the coal will behave in a flow, especially in a dense-phase flow situation in which the volume of voids is substantially reduced. In the static situation, as in a storage, consolidation can occur which decreases the permeability of the coal. This same type of phenomenon can exist in dynamic situations when pressurization either local or overall exists. This can lead to such problems as arching, ratholing, clumping and other flow instabilities. It is also thought that intermittent clumping in a dense-phase transport line is warning of blockage problems to come. The problems of clumpage are attributed to a reduction in permeability. The measure of permeability in the dynamic state would be a powerful tool in understanding and possible controlling dense-phase transport of pulverized coal. Regrettably, the measurement of permeability in the dynamic state is not easy or possible. However if a correlation could be found between permeability and some property which is measurable in the dynamic state a reasonable way to arrive at permeability in the dynamic state would be found. The most likely parameter to correlate permeability with is porosity or voidage. Since many of the parameters dealing with coal flowability such as particle size, distribution of size, etc. directly affect porosity it would seem a good variable to use to correlate with permeability. In addition to this, permeability itself is strongly dependant on the nature of the pore space in the medium. Probably the best reason for choosing porosity as the correlating parameter is the known ability to accurately measure it in the dynamic state. The porosity can be measured dynamically by the usage of devices such as an "Auburn" meter. These devices measure porosity using a capacitive technique which measures the volume averaged dielectric constant (Schmidt and Chapman, 1991). This works well as long as the dielectric constant for the solids, and the gas are very different. Such is the case with nitrogen and coal. The void fraction is also used to measure volumetric strain which correlate the internal strength and stress in compacted granular materials. In compressed materials the volume occupied by the solid remains the same while the volume occupied by voids is reduced.

In granular material the permeability and the porosity are separate properties but appear very correlatable. It makes logical sense that as the porosity decreases the permeability will also decrease. By correlating permeability and porosity in the static state along with measuring porosity in the dynamic state a better understanding into the behavior on-line of a coal feed system can be achieved.

2.4 Feasibility

The feasibility of this desired correlation was expected to be very good in that the principles along with the measurements are very simple and require nothing out of the ordinary lab equipment to obtain results with a high degree of accuracy. Emphasis throughout the experiment was on simplicity since this effort was intended only as a beginning or jump-off point in the fundamental understanding of the dynamic relationship between the gas and the solid in dense phase transport. The determining factor in the success or failure of this experiment was the attention to detail in the actual experimental process. The various variables discussed previous which affect the coal flowability and thus its handling were dealt with in individual ways. Some variables such as moisture were only noted but not controlled. Similarly coal rank or type was changed by using several different coal seams as sources. The particle size was changed by varying the ball mill to which a coal sample was subjected. It was also anticipated that this would strongly affect the size distribution of the particles. The porosity was changed through different compactions of the sample that was used. Through controlling some parameters while changing others the desired results lead to an insight into the role pore pressure plays in dense phase coal transport flow problems.

3.0 EXPERIMENTAL SETUP

The main purpose or objective of this study was to measure the permeability of several pulverized coals in various degrees of compaction. Along with this the bulk density was measured at the same time in order to calculate the porosity. Using these measurements, which were taken in the static state, it was anticipated that a successful correlation could be found between permeability and porosity while changing or controlling and noting other factors such as particle size, size distribution and moisture. These results then could be used to expand the base knowledge of pulverized coal transport by knowing the gas coal interaction as expressed by permeability. By using the correlation between permeability and porosity this relationship could be extended to the dynamic state where porosity unlike permeability is measurable.

The parameters to be measured in this experiment were as follows: pressure drop across the sample, weight and volume of the sample at various conditions, flow rate of gas through the sample, and visual checks for absence of fissures or cracks in the sample. Other tests were performed on the sample for particle size and size distribution, chemical contents and moisture content. Using the volume and weight of the sample at a given condition led to a calculation of porosity. The porosity was the variable which was controlled and changed by using various particle preparations and different compacting pressures. The different sample particle preparations led to different grain sizes and distributions. Two variables were only noted as characteristics of a given coal rank or family, these were chemical content and moisture content.

The variables which tend to characterize the individual samples were size and size distribution. Both of these variables were measured in accordance with American Society of Testing and Materials (ASTM) - D410-38 which describes the methodology for the sieving of coal. Sieves used in these experiments were from 50 to 400 mesh in size. The three families or seams of coal used in this experiment were, Upper Elkorn coal in micronized form, Illinois #6 and Montana Rosebud. In this report we shall refer to these coals as micronized, eastern, and western for Upper Elkorn, Illinois #6 and Montana Rosebud, respectively. Of these coals only the micronized was not sieved. This coal was too small to successfully be sieved in addition to the fact that good size and distribution data already existed. The western coal was sieved but due to its higher moisture content it did not sieve very well and tended to agglomerate or clump thus sometimes causing inconsistent results. Wet sieving was tried but it is the belief of the lab and the author that the results of this technique were difficult to acquire and probably not very accurate. For these reasons most of the experiments were done using Eastern coal.

The true solids or baseline density was also needed in order to calculate porosity. This was accomplished in accordance with ASTM - D410-38 which is a liquid displacement test for measuring the density of an actual solid piece of material. This test did present a problem in that the finer grinds of coal which were used tended to float in the liquid methanol used as the liquid medium.

After some discussion and agreement that the assumption that a coarsely ground coal particle or chunk was not very porous, it was decided to use very coarsely ground particles to perform these tests. This worked well except for the micronized coal for which no chunks of greater than micronized coal size existed. Therefore since the micronized coal was more similar to the Eastern coal, the true solids density of the Eastern coal was used for the micronized coal as well.

The characteristic variables of chemical and moisture content were also measured using standard ASTM lab procedures of D3173-73, D3174-82, and D3178-73. In addition, one particular sample was subject to before and after moisture test to check to see if the passage of the N_2 gas used in the permeability studies had a noticeable drying effect.

The actual preparation of the coal samples was the key process in obtaining varying values of porosity. The primary variables which were varied were size and size distribution. In order to achieve this, samples of coal were ground in a ball mill for differing periods. It was believed that this method would provide good results while avoiding the problems of preserving the coal and then making up individual samples. This also would more closely simulate the expected distribution of particle size. The two coals that underwent this grinding, eastern and western, were first chip ground using a jaw like mechanical grinder which reduced the coal in size from that typical of a piece of gravel to the size of a typical large grain of sand. This coal was still very coarse by pulverization standards. The coal then was loaded into a 10" diameter by 7" high rotating ball mill which was approximately half-filled with coal and half-filled with 1" diameter ceramic balls. The crock or container was then put on rollers which caused it to rotate at approximately 60 cycles/sec. The grinding times of individual runs were varied. These grind times along with their coal type became the identifying characteristics of the individual coal samples. Coal was removed during this grinding to achieve the varied grinding times. Usually approximately 1 l of coal was removed at a time with this being an approximate figure due to the coals differing fluffiness at times. It is important here to remember that his process was designed to achieve varying particle size and size distribution. Therefore it should not be too surprising that the coal preparation didn't need to be repeatable or predictable.

The physical set-up which was used to measure permeability is shown in Figure 5. This set-up was the result of evaluation and in many cases simplification of the three required functions of the equipment; measuring, metering, and containing of the sample and gas flow. The basic components of this system used to contain the coal & N_2 gas included a 24 inch long glass tube of 1.206 inches inside diameter and 1.426 inches outside diameter. The tube was sealed at either end with a flange, that had the same I.D. as the tubes O.D.. A rubber gasket was placed between the tube and the flanges for sealing. The flanges, were attached to the tube by four threaded rods parallel to the tube outsides which were tightened to force the flanges to compress the rubber gaskets. These flanges were fastened to flanges which contained tubes for inlet gas and gas outlet on their respective ends and ports for pressure

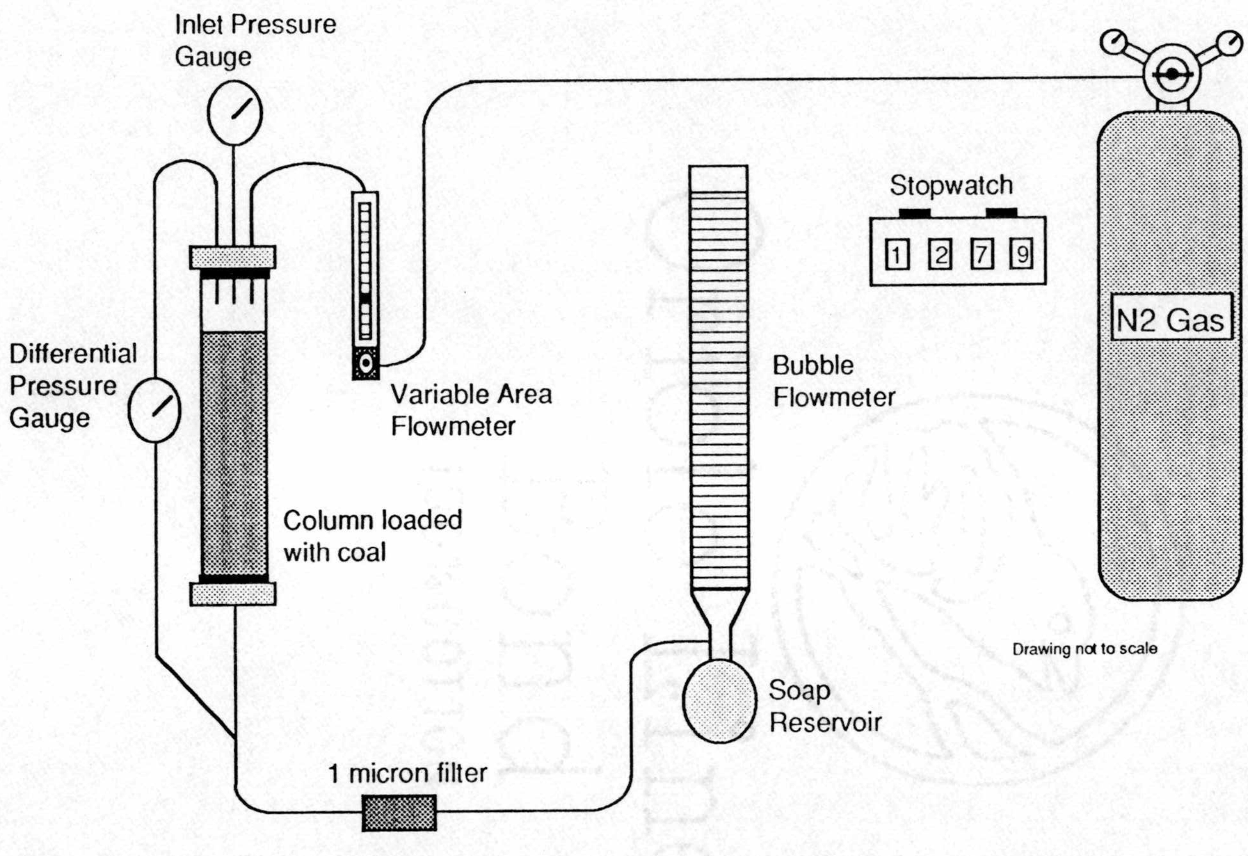

Figure 5. Experimental Apparatus

measurement. Rubber gaskets were also used in the flange to flange connection. Using this apparatus the tube could easily be removed, unloaded, and loaded with a new coal sample in a few minutes. Even with all of the changes in coal samples no leak was ever found in the tube to flange connection. The gas used for these experiments was N_2 gas contained in a bottle of 99.99% purity. This bottle gas system was chosen due to its purity and convenience. Also the amount of gas withdrawal was so small that a bottle could easily supply enough gas for the entire experimental program. The gas was supplied to the glass tube at varying pressures depending on the test conditions through $^1/_4$" teflon tubing. The only other components used to contain and control coal and N_2 were filters located in the attaching flanges. It was anticipated that a very small Gore-tex or other very small porous fabric filter would be required. Much effort was put into some preliminary coal containment tests due to the fear of coal escaping and contaminating all the measurement systems attached to the apparatus. Fortunately this was not a problem and a standard paper #2 or #4 filter proved to be sufficient at an insignificant pressure drop in relation to the pressure differential across the coal sample itself. As a safety precaution a 1 micron filter was attached downstream of the sample tube for protection in the event of an upstream filter failure.

Another basic function of the experimental apparatus was the metering of the N_2 gas flow itself. The system required very low flow rates in order to achieve pressure drops in the range of approximately 2 psi to 30 psi across the sample. The use of standard needle and ball values proved to be difficult and as a result the adjustment of the gas flow was impossible no matter what the supply tank outlet pressure setting. After trying a wide variety of valves and pressure regulators, a variable area glass tube flow meter was tried.

This flow meter proved to be very good for flow regulation and ease of adjustment due to the low flow valve it was equipped with. This flow meter was satisfactory as a regulator and controller of flow but was not satisfactory as a flowmeter due to the fact that the scale range of the meter itself was less than the required flow range of the equipment.

The last of the required basic functions of the apparatus, measurement was the most involved. To measure permeability, the simultaneous measurements required were the pressure drop across the sample and flow rate of gas through the sample. To measure the porosity the volume of the sample, which depended on the height of the column, and the mass of the sample had to be determined. To measure flowrate several different approaches were taken. The first of these was the use of time averaged water displacement as shown in Figure 6. This system measured the flow by measuring the time it took for the gas flow to displace a given amount of water. This system of measurement quickly proved to be become very cumbersome. The flow rates were so low that the water head seemed to have an effect on the measurement. Also the system required constant refill of water in addition to short run times which hampered on line adjustment of other parameters. The next evolution of the flow rate measurement involved the use of a flow element which measured flow rate using a hot wire anemometer and orifice. This device

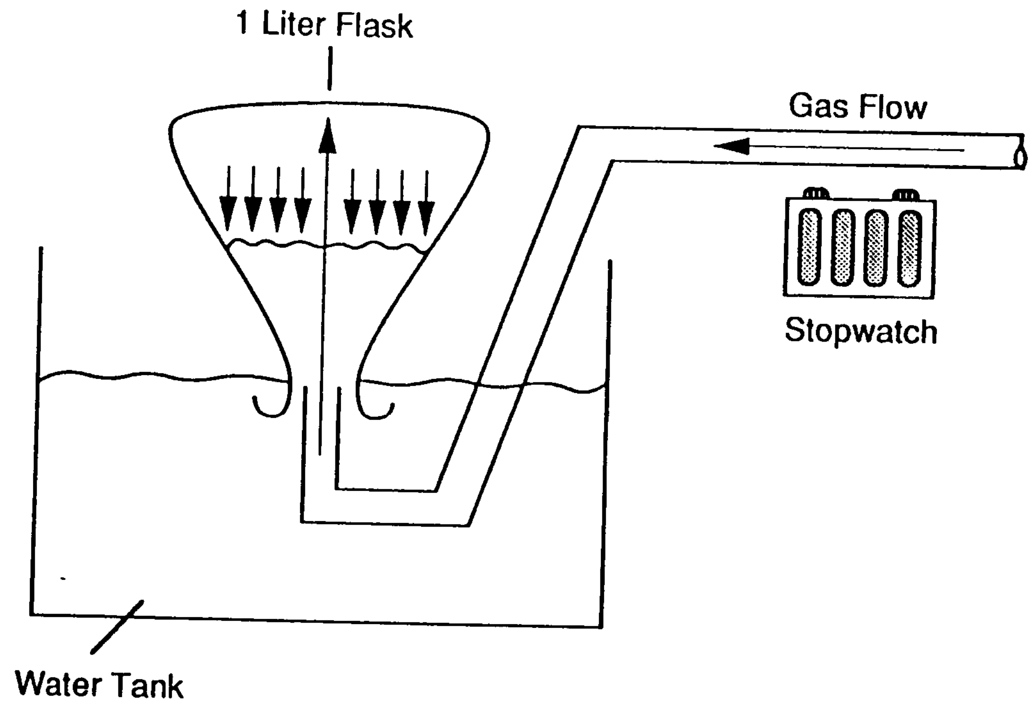

Figure 6. Schematic of Water Displacement Flowmeter

output a DC voltage which could be converted to a flowrate using a calibration curve. This system, when operating well and within its range, worked well, however, the elements tended to malfunction, not hold calibration and were often in need of repair. Throughout this process a bubble meter had been used for calibration. This meter works by bringing the gas into the side of a graduated cylinder which has a bulb filled with soap located at the bottom. When a flow measurement is to be taken a bubble is pushed out of the bulb into the gas flow path and its time to travel between graduation on the cylinder is recorded. Since this bubble meter worked well as a calibration standard and was very adaptable to the apparatus configuration it was decided that it would work very well as the actual flow measurement device. The bubble element performed rather well. The only small problem occurred in the selection of a bubble source liquid. After trying everything from dish liquid to childrens soap bubbles, "snoop leak detector" turned out to perform the best. Two different graduated cylinders of 25 ml and 500 ml capacity were used depending upon the flow rate. This was dictated by the time it took for a bubble to travel the length of the tube along with the sometimes severe deformation of a bubble when the linear speed was too great. This bubble meter although simple worked very well and had a high level of repeatability.

The measurement of pressure drop across the coal sample was accomplished using a differential pressure bourdon tube gauge. Originally a 0-20 psi Orange Research gauge was used. This gauge proved to have too course a scale and thus made reading pressure changes very difficult. A 0-35 psi Wallace and Teiron gauge was used which read in increments of 10 psi. This proved much more sensitive and improved the repeatability of the results.

In order to calculate the porosity, the volume of the sample and mass of the sample had to be determined. The volume was measured by measuring the height of the column and multiplying by the cross-sectional area. The height was measured using a scale beside the tube. There is some source of error in that the coal sample was not always level and therefore some approximation of its average height had to be made. The mass of the sample was measured using a balance scale.

3.1 Procedure

The procedure used in the experiment, like the equipment, was a result of many changes and iterations aimed toward attaining good results on a regular basis. The first task was to load the coal into the tube and insure that it contained no cracks, fissures or discontinuities. The best method discovered to aid in establishing coal uniformity was to allow sufficient settling time. The coal was allowed to settle for 1 hr after each loading to allow any trapped gas to escape and for the coal to settle. If the coal was not allowed to settle as was the case on one occasion discontinuities or cracks could form as shown in Figure 7. This sample was thus discarded. A viable question of this experiment was whether the coal would compress uniformly upon introduction of the pressurized gas. This question was answered by using tracers in the coal

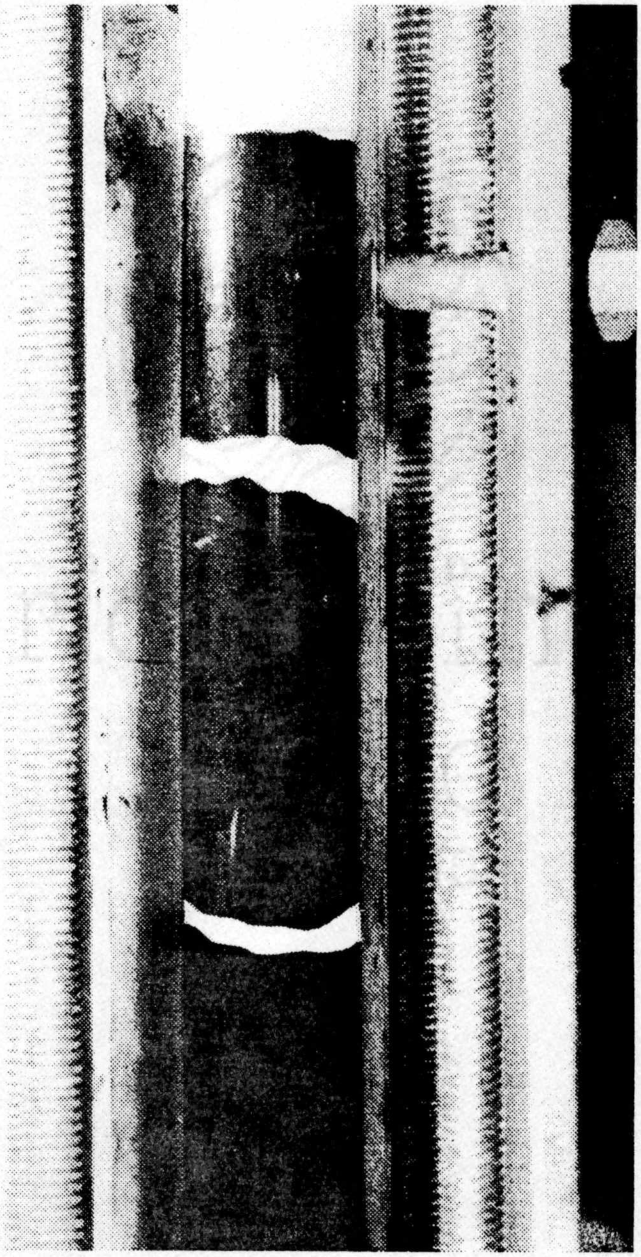

Figure 7. Cracks Due to Non-Settling Before Compaction

column. The tracer chosen was flour which was intermittently layered in the coal column as shown in Figure 8. The distance of the flour layer from the bottom of the column was measured both before and after the imposition of the pressure. Several layers, were spaced throughout the tube and measured. This experiment was performed twice with results which indicated uniform compaction as shown in Table 1. The important parameter here is the percent amount of compaction and its relative uniformity. In this table the first column gives the original uncompressed height, the second column the compressed height, and the third column the ratio of compressed to uncompressed height. From Compaction Test II for example the overall compaction was 13.8% while the average for each layer was 11.2% which includes the bottom most layer in which measuring error can play a more significant role. A similar result exists for Test I.

After loading the coal into the test apparatus in such a manner as to insure uniformity, the coal sample was ready for compaction. In compacting the coal several different methods were planned. One method was to compact the coal from both ends using a mechanical piston on either end of the column. Another compaction scheme, which was planned only as a preliminary test method, simply consisted of using the pressured N_2 gas itself as the compacting media. In this method an inlet pressure to the coal was chosen with the exit being at atmosphere conditions. The inlet pressure was slowly raised from zero gauge to the desired pressure in a smooth fashion usually taking approximately 5 minutes depending on the desired final pressure. The coal sample never was

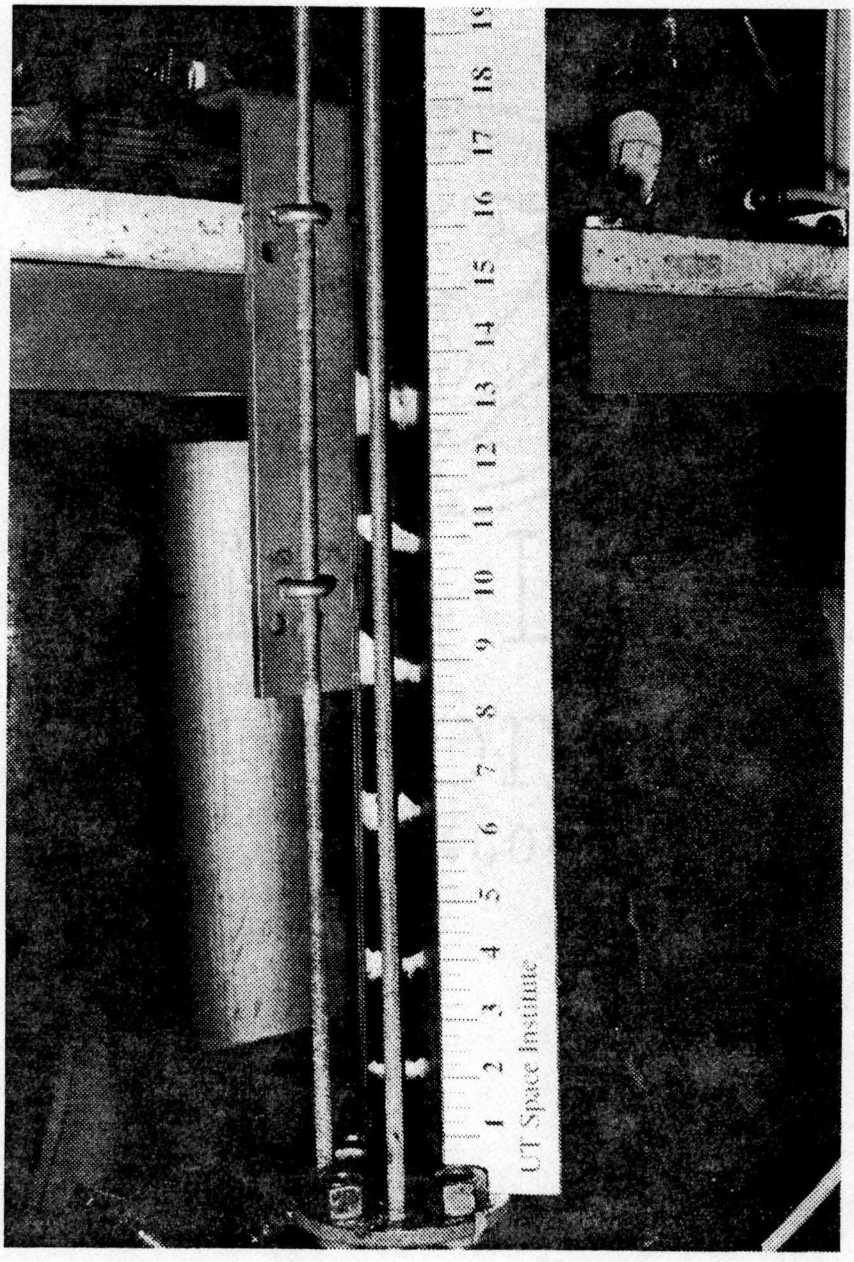

Figure 8. Uniformity of Compaction Tests
Using Flour Tracers

Table 1. Results of Uniformity of Compaction Tests

Compaction Test	Original Height (in)	Compressed Height (in)	Compaction Ratio
I (7 psi)	3 1/8	2 13/16	0.900
	7 1/8	6 3/16	0.868
	9 1/4	8	0.865
	10 15/16	9 1/4	0.846
	12 3/4	11	0.863
	18 1/2	15 11/16	0.848
II (10 psi)	2 9/16	2 7/16	0.951
	4 3/4	4 1/4	0.890
	7 3/4	6 3/4	0.871
	10 9/16	9 1/4	0.876
	12 15/16	11 3/8	0.879
	15 7/8	13 11/16	0.862

subjected to pressure in a dead headed tube. The sample was also allowed to stabilize for several minutes after the pressurization. If the pressure was raised too quickly the pressure gauge measuring the pressure drop across the sample would jump and coal would separate as it tried to compress too quickly causing pockets of gas to be trapped. This method of using the N_2 gas as the compacting media worked so well that it was decided to continue using it throughout the experiment as long as the pressure was applied slowly as described above.

Once the coal sample compaction process was completed the average height of the compressed column was recorded. The gas flow rate then was measured using the bubble flow meter by taking 10 measurements at a pressure setting. Two flow measurements were taken at a time by measuring the time elapsed for the same bubble over two different displacements. This was done to try to help eliminate spurious readings due to changing conditions, i.e., a dry bubble tube or poor time measurements. Five of these two reading sets was taken in order to get a good average value for volumetric flowrate at a given pressure.

After taking these flow measurements at the compaction pressure the inlet pressure was lowered by 1 or 2 psi depending on the compaction pressure and additional flow measurements were taken in a similar fashion. This was repeated until the inlet pressure was lowered to between 2-5 psi gauge depending upon the initial pressure. Two facts are significant to note. The first is that the inlet gauge pressure always equaled the pressure drop across the sample. This is due to the fact that the outlet pressure was atmospheric. This fact was monitored by a pressure gauge which read the pressure above the coal sample. In every case this gauge read the same value as the pressure differential gauge which measured the pressure drop across the sample. The other fact was that after compaction, at some initial inlet pressure, the coal die not spring back upon the lowering of the inlet pressure. Once compacted the coal could only be further compacted by the introduction of a higher initial pressure gas.

In most other experiments or studies of permeability the inlet to the sample is located in the bottom of the container rather than the top. This is done to counteract gravitational compaction by having flow upward vertically through the sample. In this method the inlet gas is adjusted until it causes the sample to float and then is reduced to just below the floating point to make the permeability measurement. This gives a permeability measurement at maximum static voidage. Unfortunately in most cases such as feed systems the gas flow tends to compact the sample with increasing pressure causing a decrease in the void fraction. Therefore the conventional permeability measuring set-up does not allow for the measuring of permeability as it relates to increased compaction. For this reason in this experiment it was decided to have gas flow from top to bottom thus promoting compaction since it was and is a variable critical to the understanding of coal flow. The major question concerning this type of configuration is the uniformity of compaction which has already been discussed.

The accuracy of these experiments depended a great deal upon attention to detail and continuously checking for problems. The system was subjected to leak checks by using "snoop leak detection" fluid at joint points along the system. At times, different size flow meters were used solely for the purpose of verifying the results and the measurement systems were improved throughout the experiments duration in order to achieve the goal of accurate, repeatable and reliable results.

4.0 RESULTS

The results of the experiments are organized into five major areas in their presentation. The areas are: 1) characteristic variables, which includes moisture and chemical composition of the coals used; 2) feedstock parameters, which include coal size and size distribution data of the coals used; 3) porosity and permeability inputs, which include the weight of the sample, height of the sample in the column, flow rate of the gas through the sample, and pressure drop across the sample; 4) calculated quantities, porosity and permeability; and 5) correlation between variables such as porosity, permeability, particle size and size distribution. In each of these areas results, accuracy and if applicable statistics are discussed in order to give a descriptive picture of the results and their interaction.

4.1 Characteristic Variables

The first of the resulting areas was characteristic variables. These results simply give a description of the coal which was used in the experiments. These variables: chemical composition and moisture were not adjusted during the experiment. Data showing the ultimate analysis (ASTM D3176), and gross calorific value (ASTM D2105) are shown for each of the three coal types used eastern (Illinois #6), western (Montana Rosebud) and micronized (Upper Elkorn) in Table 2. In this table the important parameters to note are heating value, which determines coal rank, and moisture, which is an important factor in

Table 2. Analysis of Selected Coals

	Coal Classification		
	Eastern Coal (Illinois #6)	Western Coal (Montana Rosebud)	Micronized Coal (Upper Elkhorn #3)
% Ash	10.70	10.23	2.82
% Carbon	68.74	63.70	82.68
% Hydrogen	4.95	4.99	5.58
% Nitrogen	1.46	0.90	1.13
% Sulfur	2.59	0.69	0.64
% Oxygen (by difference)	11.56	19.50	7.15
% Moisture	5.48	5.93	0.28
Higher Heating Value (lb/MMBTU)	12643	10716	14982

coal's flowability. These analysis follow the expected trends of larger higher heating values for the eastern and the micronized coals which are bituminous coals in comparison to western coal which is subbituminous. Also the moisture content of the western coal is higher as expected. The micronized coal was deep cleaned and dried and therefore had lower sulfur and moisture content. The effect of the N_2 gas, flowing through the sample in the experiment, on moisture content of the sample was thought to be negligible and was shown to be by the before and after moisture of 62% and 54% on a particular batch of micronized coal. It was somewhat regrettable that the driest of the coals used was chosen for this test. This appeared to make the actual drying by the nitrogen more important than it actually was. It was however good to see that this drying effect is not dramatic even when using a very small diameter coal which has a very large surface area to mass ratio thus enhancing drying by the nitrogen. Also it has been shown at UTSI's CFFF that this drying effect of nitrogen on the coal's moisture is negligible.

4.2 Feedstock Parameters

The next area of the results are the feedstock parameters of size and size distribution. The parameters were varied throughout the experiment. In the case of eastern coal much effort was put into getting varying median particle sizes and distributions. This was done by varying the grinding time of 7 different samples. These samples were ground in two grinds or groups. The first group was chip ground and loaded into the ball mill for grinding. After 3, 6, 9 and 48 hour intervals coal samples were removed from the mill. The second group was chip ground and loaded into the ball mill for grinding. Samples were removed at 18, 24, and 36 hour intervals. Each sample that was removed from the mill in turn had a smaller sample taken to the lab for sieving. The results of this sieve analysis using ASTM D410-38 are shown in Table 3 and are identified by their grind time, i.e., 3, 6, 9, 18, 24, 36, 48. In this table the percent through each respective screen is presented. Since the mass mean diameter and the particle distribution were the variables of interest the sieve data was analyzed to arrive at their values. In describing the distribution it was found that the distribution of particle size followed a skewed probability or asymmetrical distribution which is characteristic of many naturally occurring or mass produced particle grinds (Zenz and Othmer, 1960). In fact the distribution closely followed the log-normal distribution. Each different sample's sieve-frequency data was plotted on log-normal probability graphs as shown in Figure 9. Using the log-normal data points a linear fit was applied in order to easily arrive at the mass mean diameter which occurs at the 50% probability point. Besides the significance of the mass mean diameter (MMD) or 50% point the slope of the line on the log-normal plot has some significance. The slope or characteristic distribution factor (CDF) measures the width of the distribution with a steep line reflecting a wider size distribution. From the equation derived for each coal sample as shown in Figure 9 this is obviously true. For example the slope of the 3 hr. ground coal's log-normal plot is 1.022 while the 9 hr. coal log-normal plot has a slope of 8284. This indicates that the 3 hr. coal has a wider size distribution

Grind Number →		1				2		
Mill Time (hours) →		3	6	9	48	18	24	36
Taylor Mesh	Size (μm)	Weight Percent Through Screen						
50	300	67.29	98.34	99.36	98.84	99.65	99.61	99.46
100	150	43.27	90.59	98.64	96.49	99.07	98.78	97.56
200	75	26.31	58.60	87.99	92.83	82.63	95.34	89.57
270	53	19.53	44.45	68.95	91.29	62.68	87.96	71.68
325	45	15.83	35.93	50.11	90.40	50.16	72.26	49.59
400	38	13.56	29.86	44.30	89.61	40.97	43.24	30.22

Table 3. Sieve Analysis of Eastern Coal

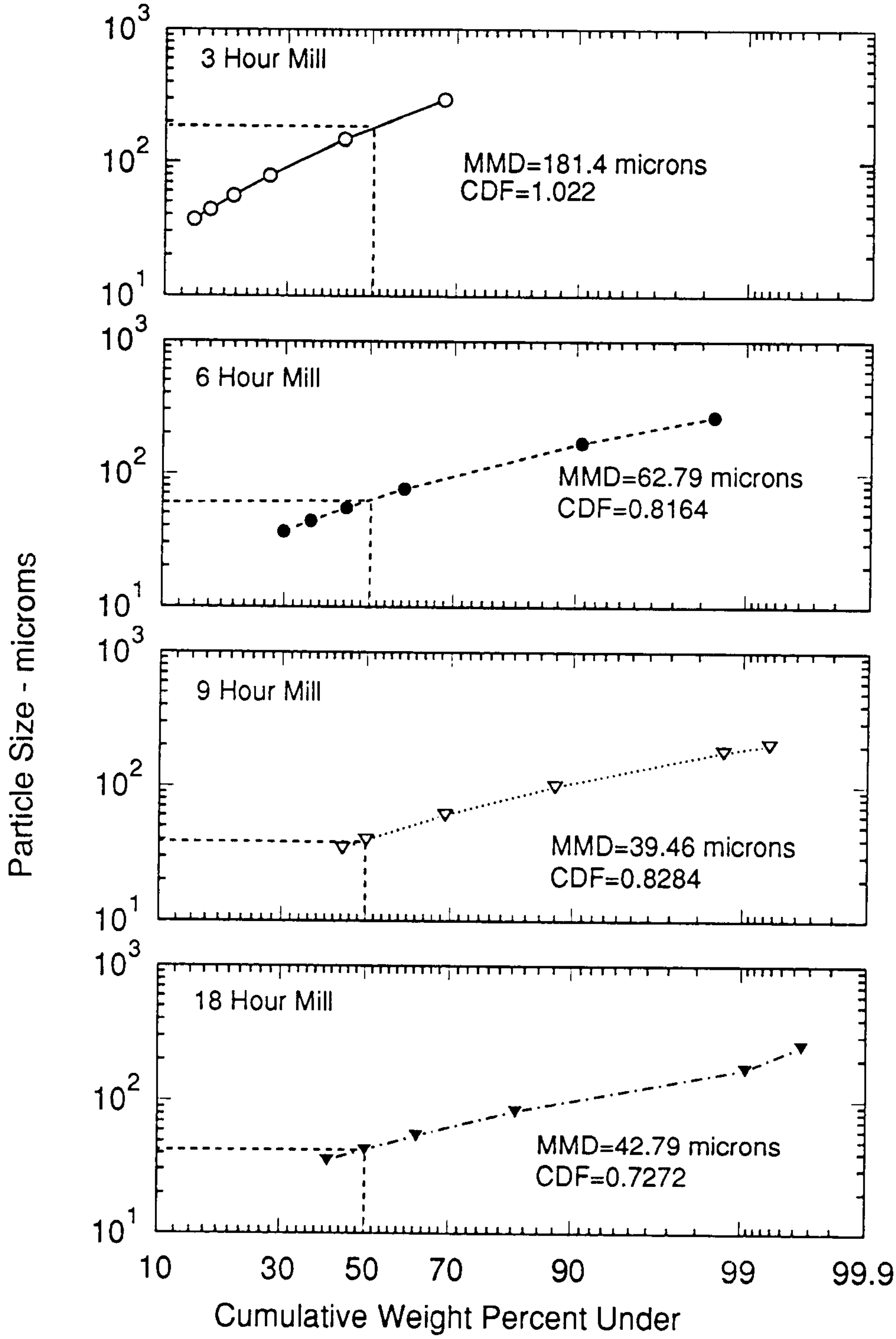

Figure 9. Eastern Coal Size Distribution

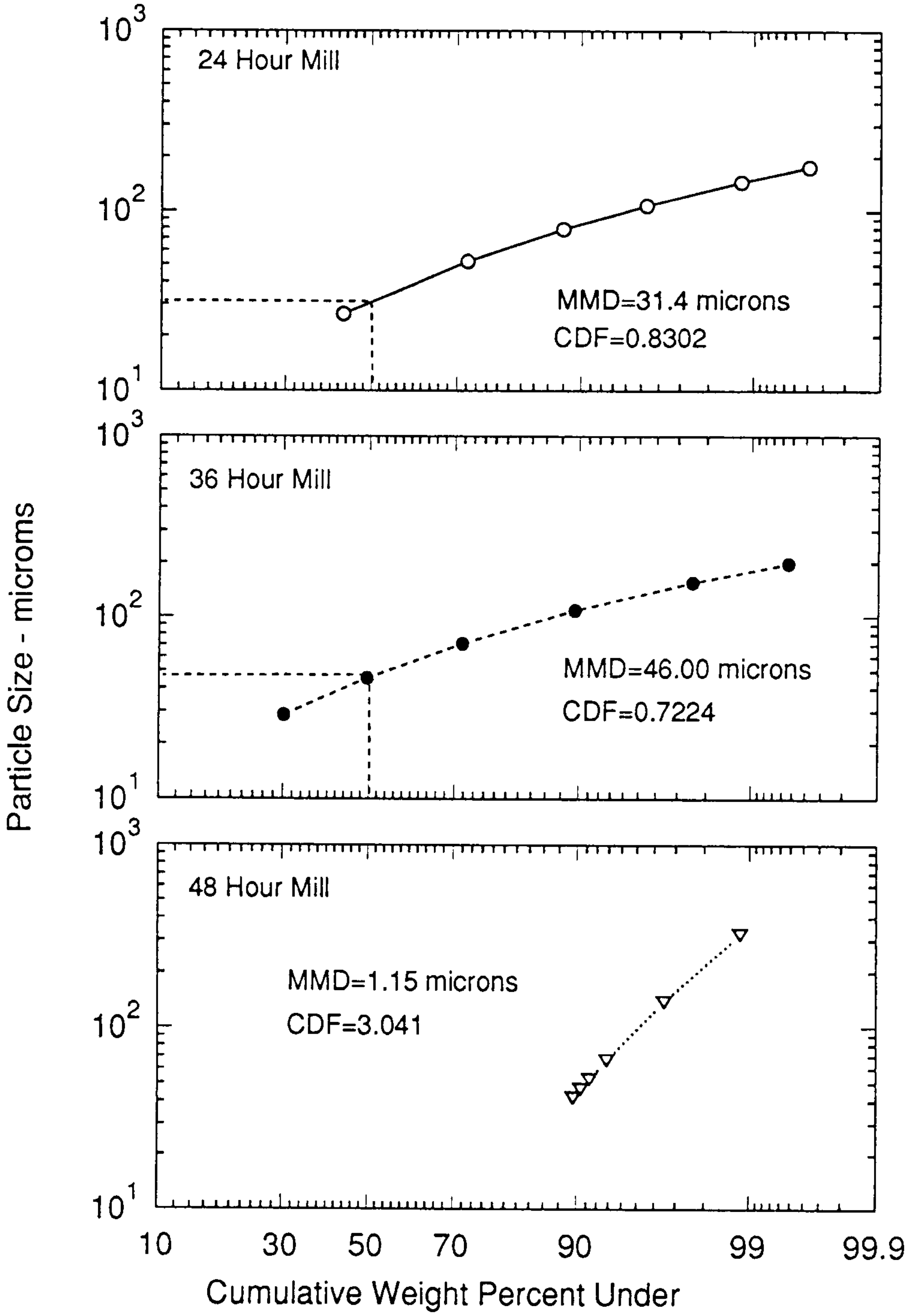

Figure 9. (continued)

than the more finely ground 9 hr. coal. The correlation coefficients "r" for the linear fit on log-normal paper range from 999 for the 3 hr. coal to 878 for the 24 hr. coal showing a good correlation to this model of particle size distribution. The mass mean diameters range from 181.39μm for the 3 hr. coal to 31.4μm for the 24 hr. coal. The mass mean diameter for each coal is also shown in Figure 9.

The western coal was only ground to one size due to the problem associated with sieve analysis encountered in the lab. The feedstock data for the western coal is shown in Figure 10 and Table 4 with the mass mean diameter being 34.6μm, the slope of the log-normal plot being 0.81562, and a correlation coefficient of 0.96. The micronized coal was too small for conventional sieve analysis and since the data already existed from ongoing Advanced Combustor test the feedstock data was as shown in Figure 11 with a mass mean diameter of approximately 10μm.

4.3 Porosity and Permeability Inputs

The porosity and permeability were determined from the results of: 1) mass of coal sample, 2) height of coal column, 3) flow rate, and 4) pressure drop. The mass of the sample was taken by measuring the mass of the column filled with coal prior to a test run and subtracting the mass of the empty column after the coal sample was removed. The balance used to measure the mass had accuracy of ± 0.25 g. The mass of the coal samples ranged from 168.25 g

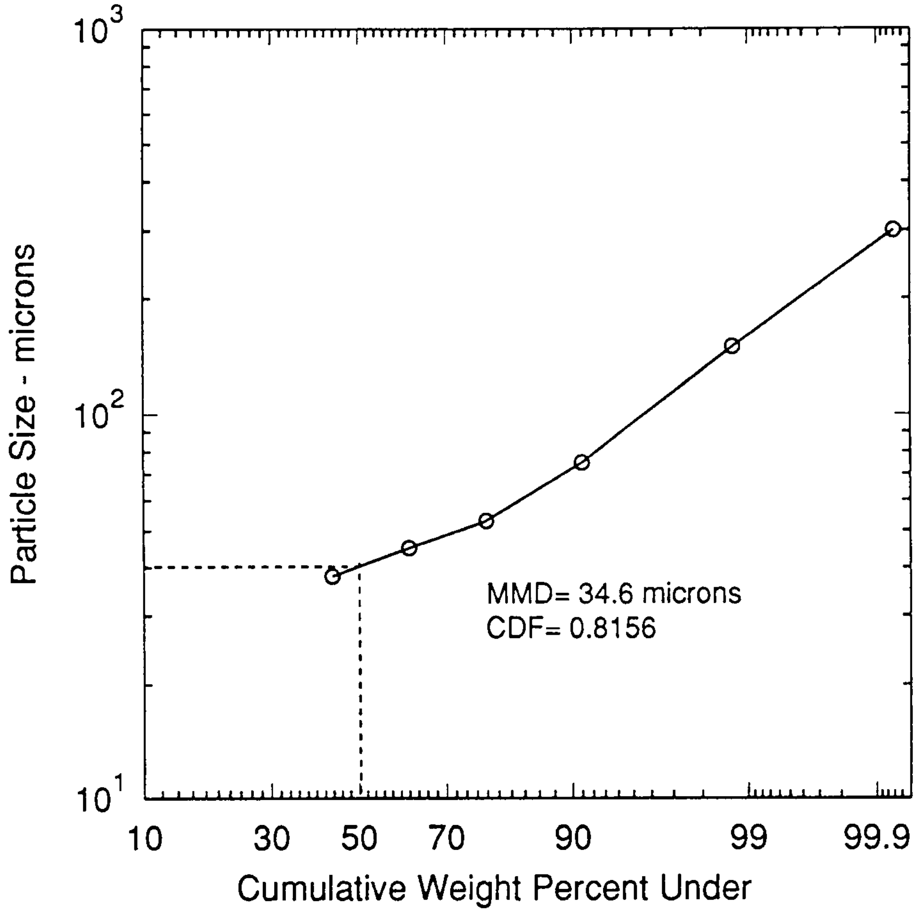

Figure 10. Size Distribution of Western Coal

Table 4. Sieve Analysis of Western Coal

Taylor Mesh	Size (μm)	Weight Percent Through Screen
50	300	99.93
100	150	98.74
200	75	91.01
270	53	77.84
325	45	61.95
400	38	43.76

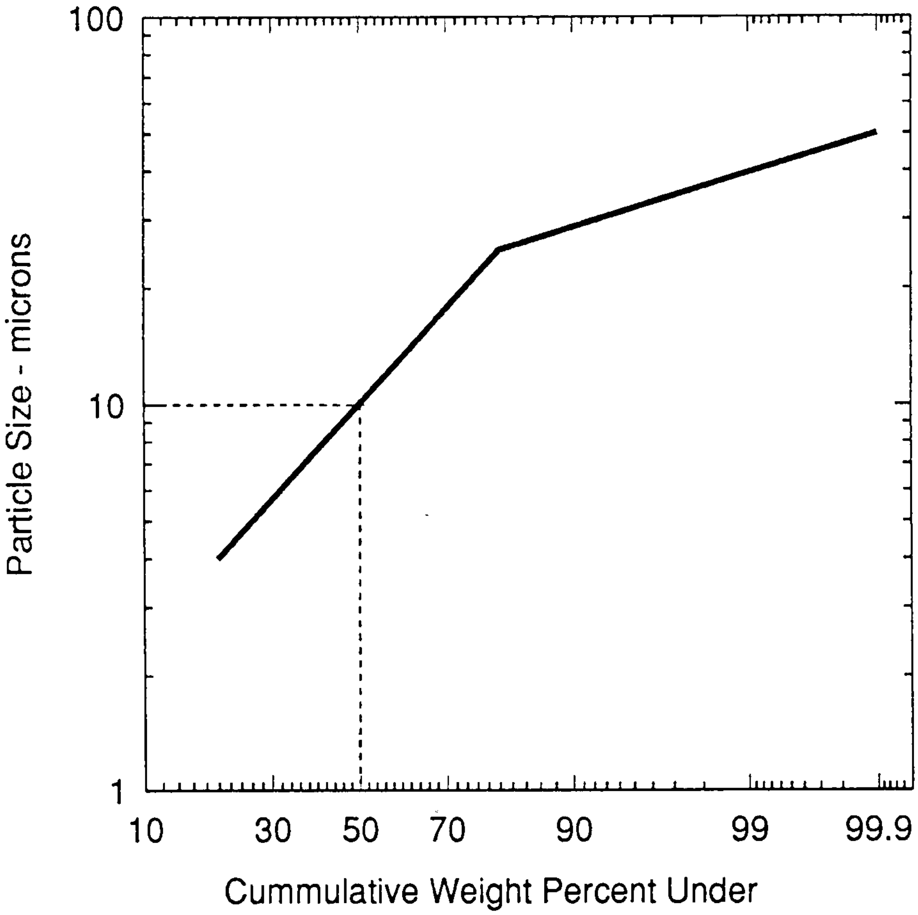

Figure 11. Size Distribution of Micronized Coal

to 273.5 g for eastern coal, 214 g to 162 g for western coal and 171.75 g to 185.25 g for micronized coal. The height of the coal column was measured after each compaction was complete. This was accomplished by holding a scale next to the clear glass coal tube which contained the coal and reading a value for the average height of the coal column. This measurement seems to be the most uncertain measurement of the experiment. This is due for the most part to the approximation of average height of a column of coal which was not always perfectly level or even surface. It is expected that this measurement was good between ± 0.25 inches. Even the accuracy of this measurement is an estimate. The height of the column ranged from 15.13" to 16.75" for the eastern coal tests, 8.5" to 12.88" for the western coal test, and 15.75" to 16.75" for the micronized coal tests. The micronized coal posed a unique problem. It tended to stick to the tube walls in such a way as to make it impossible to see the coal level after compaction. An attempt was made to measure the height in spite of this by measuring the height of a straight edge from the surface of the coal to the top of the tube and subtracting from the glass tube height. The results for both mass and length are found in Table 5 for eastern, western and micronized coal.

The pressure drop across the sample was measured using a bourdon tube differential pressure gauge which had a scale division of 0.10 psi and could easily be measured to 1/4 the scale division. This parameter was the input parameter which determined, via compaction, every result except the coal mass. The pressure drop across the coal was double checked by locating a pressure gauge which read the pressure in the glass tube above the column. In

Table 5. Summary of Experimental Results

Coal Type	Mill Time (hours)	Compaction Pressure (psi)	Mass (grams)	Length (inches)	Voidage, ϕ	Permeability, k (Darcies)
Micronized	NA	10	171.75	15.75	0.4996	0.0998
		20	185.25	16.75	0.4929	0.0862
		30	178.00	15.63	0.4776	0.0766
Western	NA	15	103.00	8.50	0.4685	0.1557
		20	214.00	17.25	0.4559	0.1494
		25	162.00	12.88	0.4481	0.1470
Eastern	3	10	273.50	18.13	0.3081	1.3093
		20	273.50	17.88	0.2984	1.2274
		30	273.50	17.69	0.2909	1.1044
	6	10	219.50	16.63	0.3946	0.7136
		20	219.50	16.31	0.3829	0.6387
		30	219.50	15.88	0.3660	0.5452
	9	10	185.00	15.75	0.4614	0.4477
		20	185.00	15.50	0.4527	0.3925
		30	185.00	14.88	0.4297	0.3185
	18	10	206.75	16.75	0.4340	0.4428
		20	206.75	16.25	0.4166	0.3880
		30	206.75	15.88	0.4028	0.3439
	24	10	176.25	16.57	0.5120	0.3164
		20	176.25	15.62	0.4828	0.2464
		30	176.25	15.25	0.4700	0.2144
	36	10	177.75	17.69	0.5392	0.2341
		20	177.75	16.38	0.5097	0.1750
		30	177.75	16.63	0.5022	0.1523
	48	10	180.50	16.88	0.5095	0.1610
		20	180.50	15.97	0.4817	0.1248
		30	178.00	15.19	0.4626	0.1020

every instance the latter pressure was the same as the previous differential pressure, as would be anticipated with a system which exits at atmospheric pressure, as would be anticipated with a system which exits at atmospheric pressure. The volumetric flow rate measurements were taken using a bubble meter and stopwatch. The flowrate was taken in five two reading sets at each flow set point. This extremely simple measurement system appeared to produce the best results of the experiment. The average flowrate along with the standard deviation for each differential pressure setting are shown in Figures 12-14 for some typical runs of each coal type. Along with this the coefficient of variation V, is defined as

$$V = \frac{\sigma}{\bar{X}} \times 100 \tag{11}$$

where σ is the standard deviation and $\bar{X}$ the average value, was calculated. This coefficient of variation was consistently at or below 1 percent thus indicating very little dispersion in the data. The good results of this measurement were independent of the coal type, condition, etc. and can be attributed to the approach used and the usage of a primary standard measuring system.

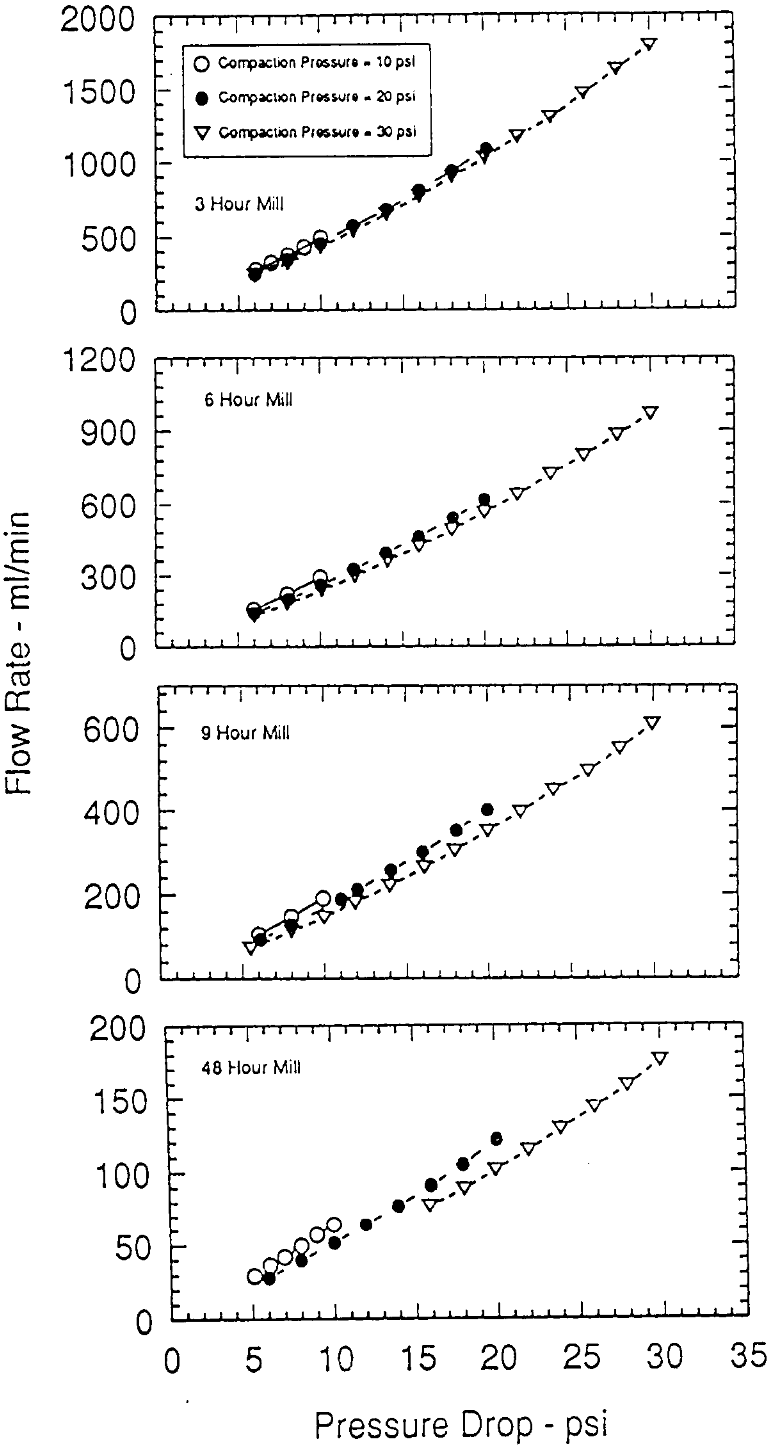

Figure 12. Eastern Coal Pressure Drop vs. Flowrate at Varying Compaction Pressures

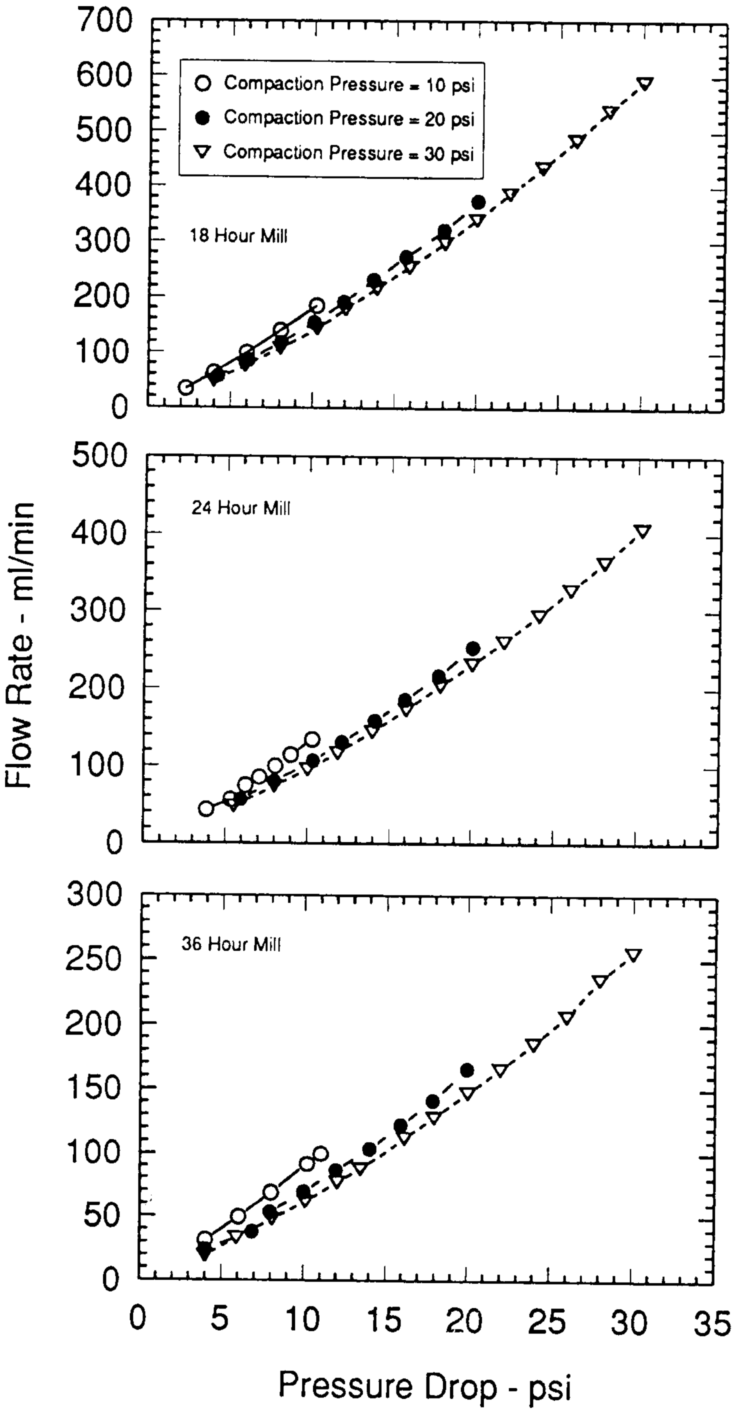

Figure 12. (continued)

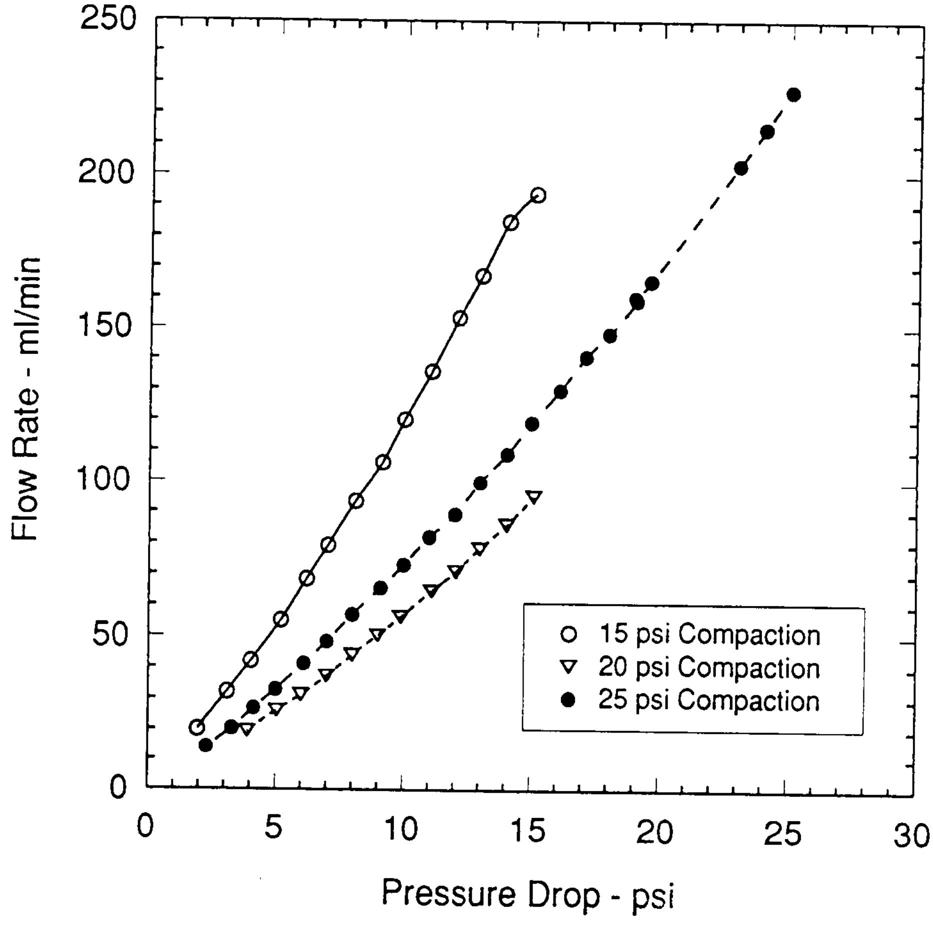

Figure 13. Western Coal Pressure Drop vs. Flowrate

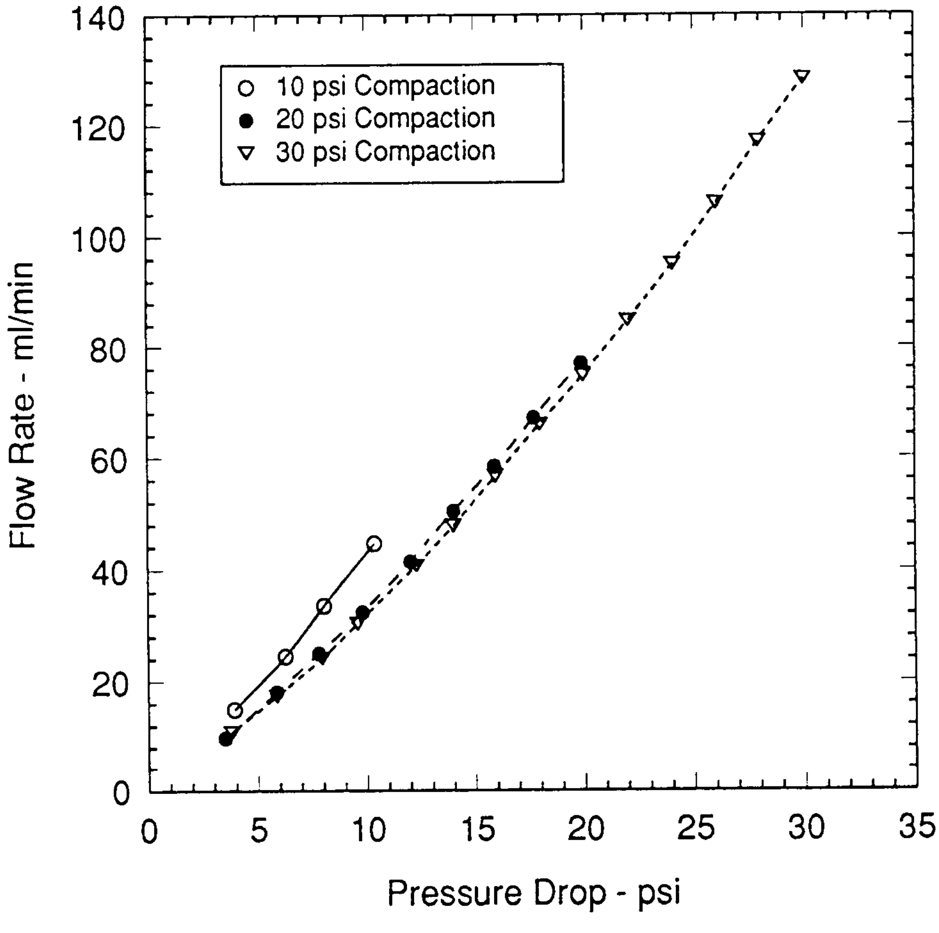

Figure 14. Micronized Coal Pressure Drop vs. Flowrate

4.4 Calculated Quantities

The next segment of the results deals with the calculated quantities of porosity and permeability. These are the two quantities in which we have the most interest. The porosity or voidage was calculated using the following relation

$$\phi = 1 - \frac{\rho_b}{\rho_s} \qquad (12)$$

when ρ_b = bulk density of the sample at a given compaction and ρ_s = density of the grain particles, ρ_s was found by using ASTM-167-73 and was found to be 1.165 g/cc for Eastern coal and 1.218 g/cc for Western coal. The ρ_b was calculated using the mass of the sample, height of the sample, and cross-sectional area of the glass tube. A voidage of zero would be expected for solid material and a voidage of 1 for a gas only situation in which no solid was present. The voidage depends solely upon density which in turn depends largely on column height and volume. This measurement is very sensitive to the height of the column. The results for voidage are shown in Table 5 (page 58) for each of the different condition coal experiments. The voidage results for the eastern coal ranged from 0.29 for 3 hour coal with a mass mean diameter of 46μm compacted at 10 psi. For western coal the voidage ranged from 0.45 to 0.68 for the 20 psi and 5 psi compactions respectively. The micronized coals voidage ranged from 0.47 for the 30 psi compaction to 0.499 for the 10 psi compaction. The permeability (k) was calculated using Darcy's Law.

$$k = \frac{q\mu}{A\,(\Delta P/L)} = \frac{q\mu L}{A(\Delta P)} \qquad (13)$$

Since μ, the viscosity of the flowing fluid, is constant for the constant temperature, A, the area of the granular solid, is constant and the length L of the column is constant for a given compaction, the permeability, k, is the relationship between the volumetric flow rate, q, and the pressure drop across the sample, ΔP. This is how permeability was calculated. As seen from Darcy's law this relationship should be linear, and the results show that it was. The linear fit for q vs. ΔP in every experiment was very good with the correlation coefficient "r" being greater than 0.996 in every instance. Over the range of each experiment Darcy's law held very well. This in part was due to its dependency on ΔP and q which as mentioned earlier are the most accurate of the experimental measurements. The results for permeability were calculated at a pressure drop of 10 psi in order to give a common comparison point. These results are shown in Figure 15 with the permeability in darcies for eastern coal ranging from 1.3 for a 3 hour coal to 0.1 for 48 hour coal. The range in darcies for western coal was 0.14 to 0.16. For micronized coal the permeability ranged from 0.076 to 0.099 darcies. In every instance the permeability decreased with increased compaction. Also the effect of particle size is seen with smaller sized particles resulting in lower permeabilities.

4.5 Comparison and Correlation

The last portion of the results deals with comparison and correlation. It was the object from the outset to be able to infer permeability in the dynamic state by correlating with a parameter which could easily be measured dynamically. Thus if the correlation could be done statically where permeability is easy to measure this parameter could be used to determine permeability dynamically, thus enhancing the basic understanding of the coal-gas interaction in dense-phase coal flow. The parameter chosen was porosity due to its simplicity and dependency on many of the factors which influence permeability. In this portion of the results we will show the relationship between particle size, and size distribution with porosity and permeability.

The mass mean diameter (MMD) should have a strong affect on porosity. As previously stated in Section 2.1, the porosity or voidage should increase as the particle size decreases. To investigate this the porosity vs. MMD was plotted in Figure 15. In this figure which represents the porosity vs. MMD for each of the seven different eastern coal preparations, the general trend is that as MMD decreases porosity increases. This can be shown better by looking at the data for 3, 6, and 9 hour eastern coal which have MMD's of 181μm, 62μm,

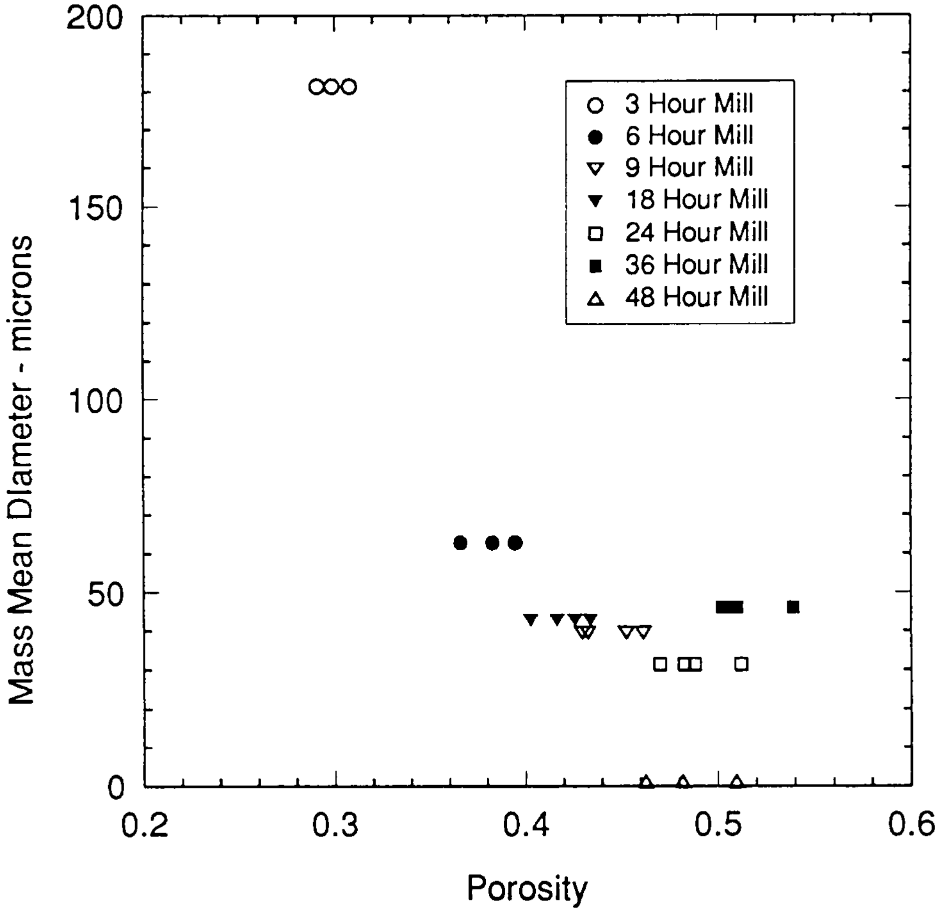

Figure 15. Eastern Coal Porosity vs. Mass Mean Diameter

and 39μm, respectively. While the other coals, 18, 24, 36, and 48 are tightly bunched between 30μm and 50μm therefore not showing this trend as clearly.

The characteristic distribution factor, which is the slope of the particle size analysis line on a log-normal probability plot, should also have a strong affect on porosity of a granular material such as pulverized coal. As the width of size distribution increases, CDF will also increase. As discussed in Section 2.1 material with a wider size distribution will tend to pack more efficiently resulting in lower voidage. To investigate this for these experiments the CDF is plotted against voidage in Figure 16. It should be noted that the 48 hour distribution data is not a very good representation as a large percentage (90%) passed through the finest screen. To see the anticipated trend an examination of the 3 hour (CDF = 1.02), 6 hour (CDF = 0.8160) and 18 hour (CDF = 0.727) coals shows that as the CDF increases, indicating a wider distribution, the voidage decreases.

The affect of MMD on permeability is shown in Figure 17. This figure shows the relationship between MMD and permeability for the seven different eastern coal preparations. The general trend is that as mass mean diameter increases, so does the permeability. This is seen better by once again looking at the 3, 6, and 9 hour coal whose MMD covers a wider range. For these three preparations the trend of increasing permeability with particle size is shown.

Figure 18 shows the relationship of CDF and permeability for the eastern coals in this experiment. Similar to the relationship of MMD and permeability

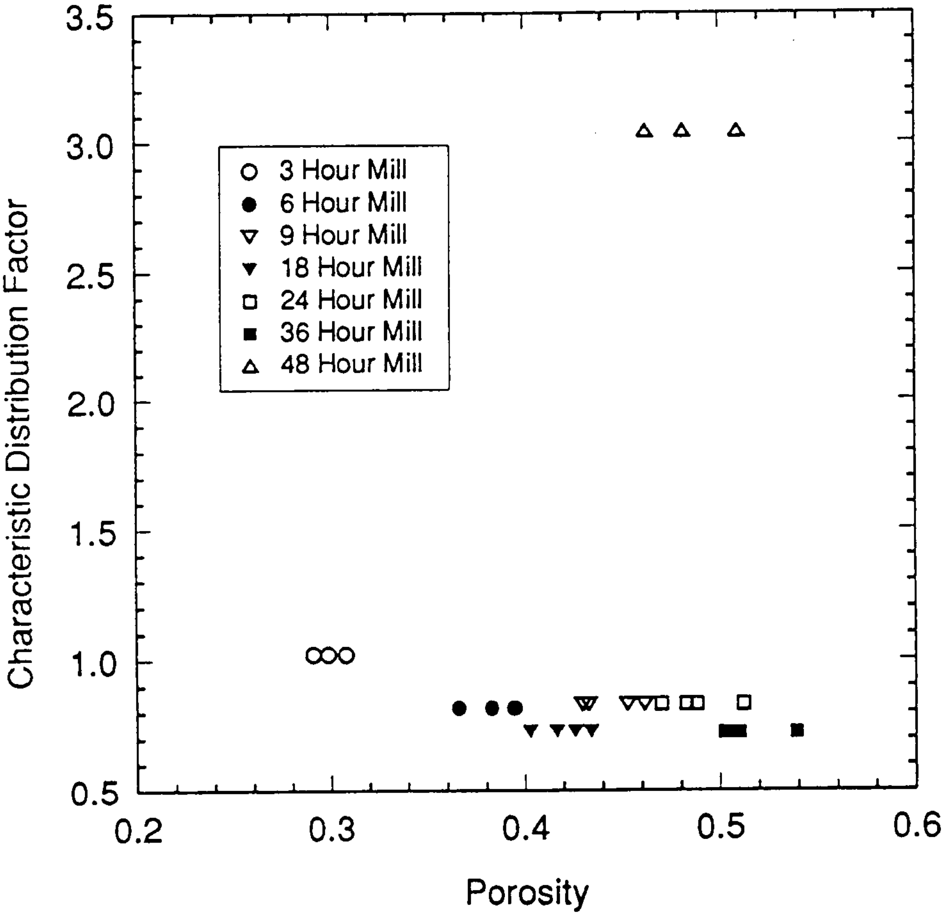

Figure 16. Eastern Coal Porosity vs. Characteristic Distribution Factor (CDF)

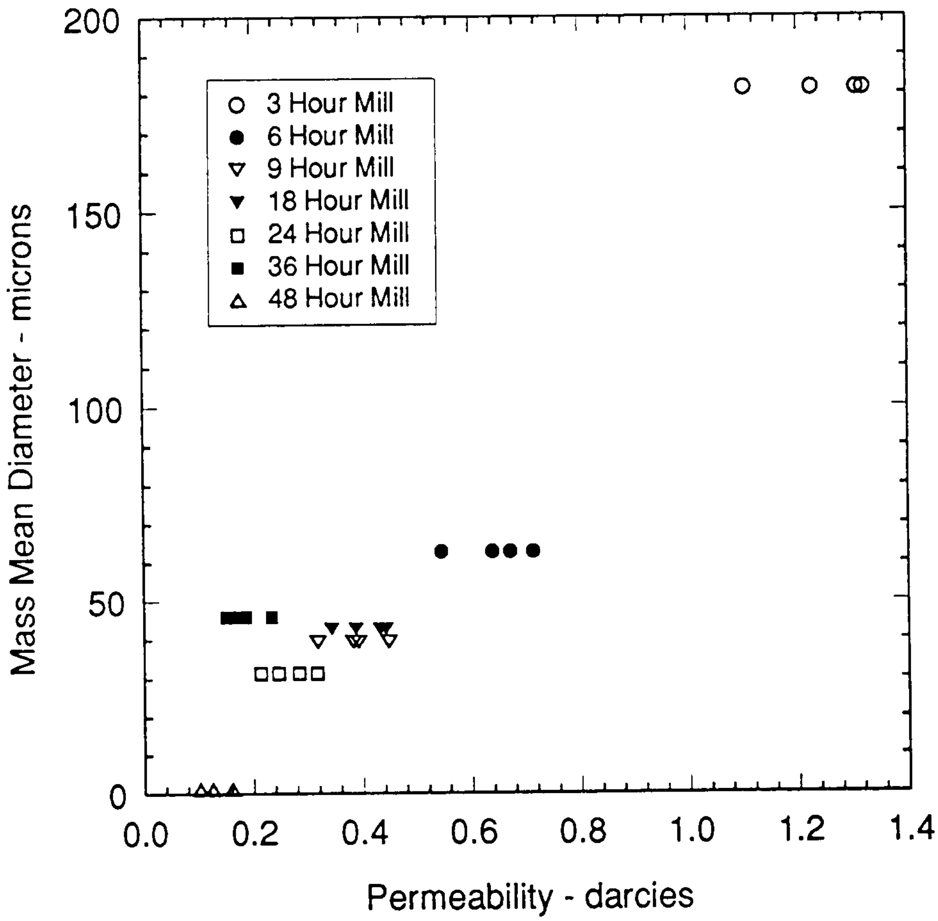

Figure 17. Eastern Coal Permeability vs. Mass Mean Diameter

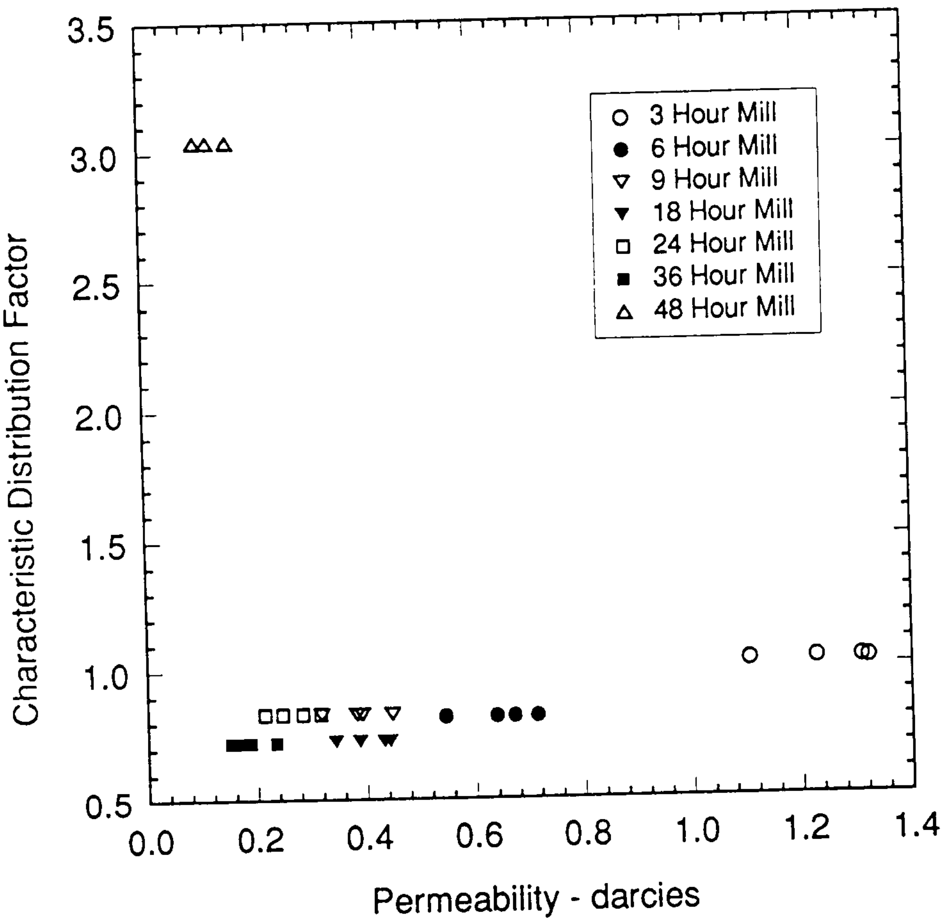

Figure 18. Eastern Coal Permeability vs. Characteristic Distribution Factor (CDF)

the 48 hour data should be disregarded due to 90% passing through the finest screen. A closer look should be taken at the 3 hour (CDF = 1.02), 6 hour (CDF = 0.8160), and 18 hour (CDF = 0.727) which cover a wider range of CDF's. Upon a closer look at these data points we see a general trend of increasing permeability with wider particle size distributions.

The desired relationship of this experiment was the static relationship of porosity (voidage) to permeability. This relationship is shown in Figures 19, 20 and 21 for each individual coal preparation at the three different levels of voidage for each, at a given ΔP of 10 psi. In every case the porosity affected the permeability as expected, i.e., the permeability increased as the voidage increased. The relationship was linear with very good correlation coefficient, r of 0.99 or greater except in two cases in which r = 0.985 and 0.95, with the r = 0.95 being the hard to measure porosity of micronized coal.

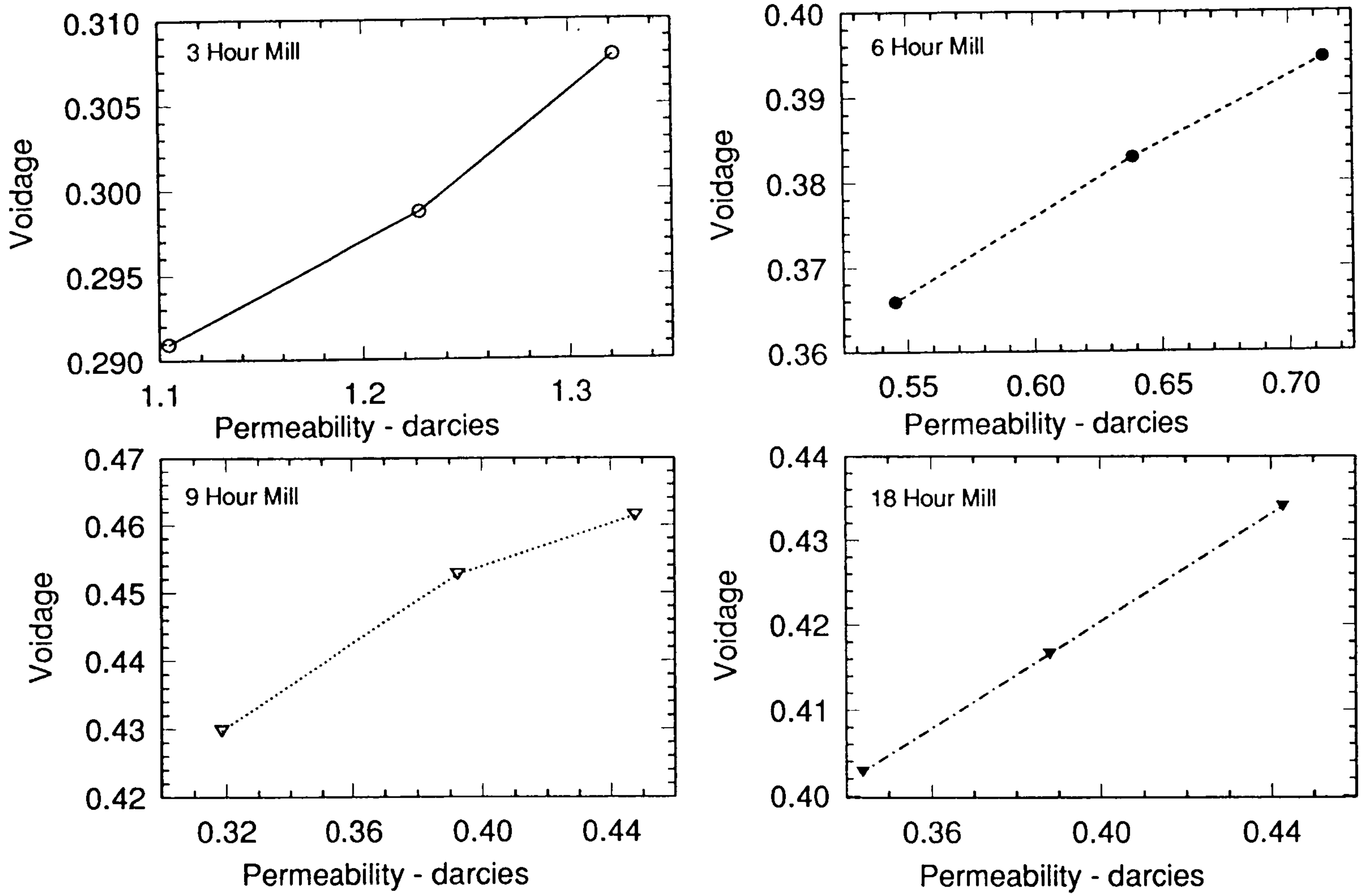

Figure 19. Eastern Coal Voidage vs. Permeability
at 10 psi Pressure Drop

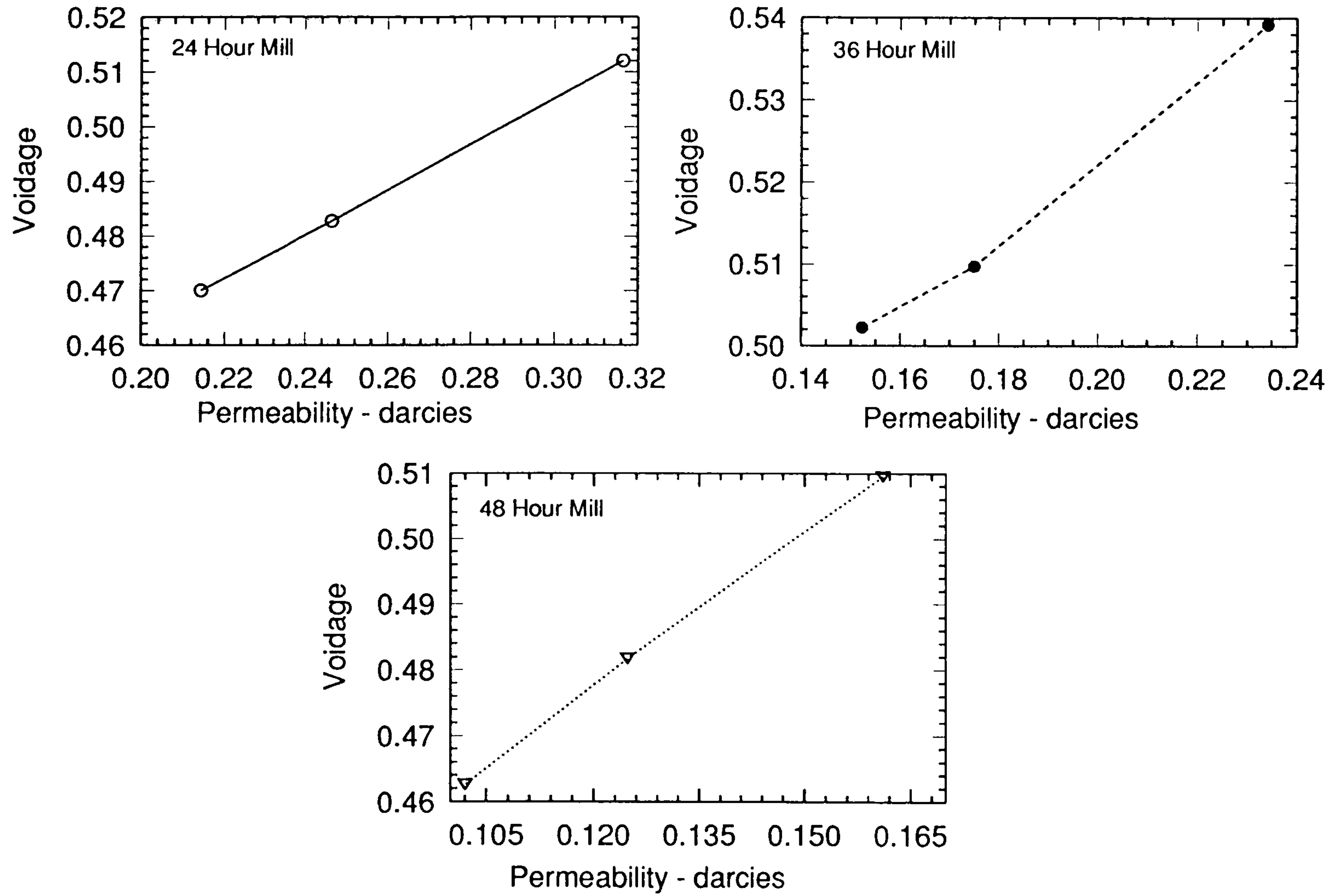

Figure 19. (continued)

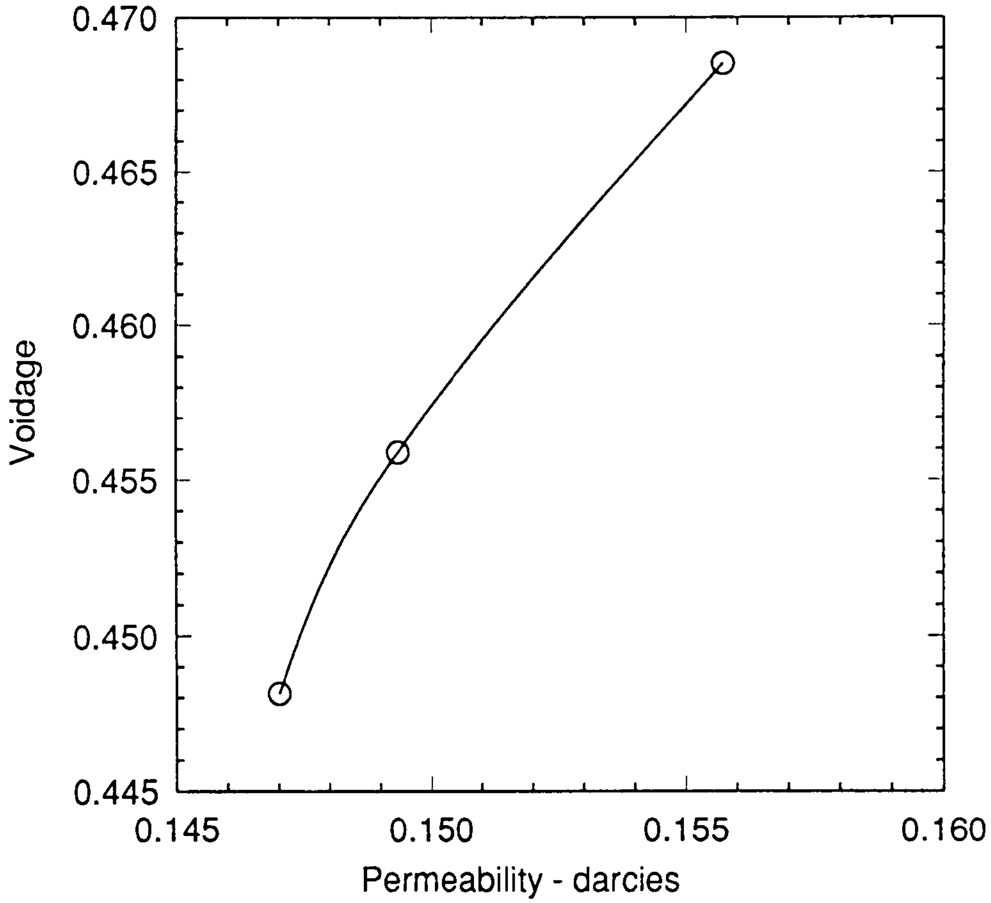

Figure 20. Western Coal Voidage vs. Permeability
of 10 psi Pressure Drop

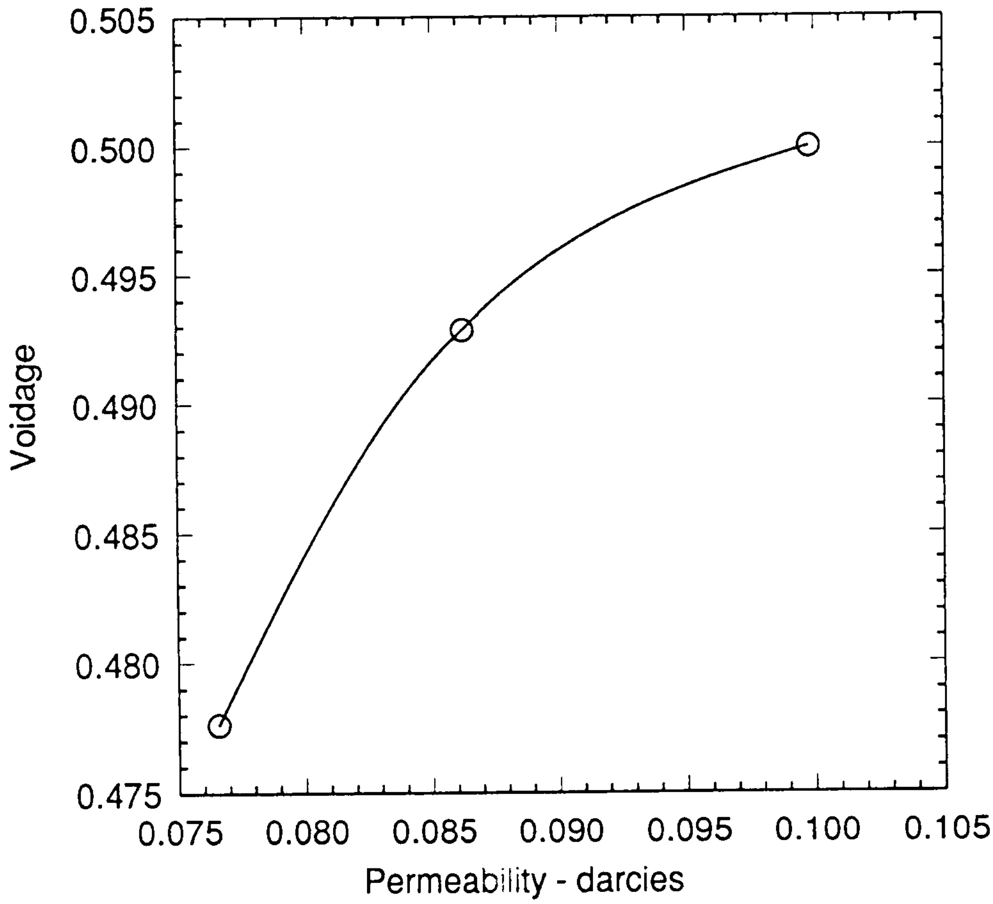

Figure 21. Micronized Coal Voidage vs. Permeability
at 10 psi Pressure Drop

5.0 CONCLUSIONS AND RECOMMENDATIONS

In this investigation the goal was to correlate porosity and permeability in the static state with the longer range goal of extending this to the dynamic state where porosity unlike permeability is a measurable quantity. Porosity as expected was very dependent on the particle size and particle size distribution. This led to confirmation that porosity is a valid variable to correlate with permeability due to its strong dependency on two important characteristics of pulverized coal in dense-phase flow. As stated in the results the relationship between porosity and permeability within a given coal preparation was very strong and should serve as good ground work knowledge in understanding the dynamic relationship between porosity and permeability.

Even though these individual coal preparation results were as expected the composite results of all of the eastern coal tests were not as first anticipated. The results as shown in Figure 22; show a surprising trend of increasing permeability with decreasing voidage. A similar trend was also seen in the mass mean diameter (MMD) data. In this data the permeability increased with the MMD even though the voidage decreased. The particle size distribution (CDF) data also, but somewhat less dramatically, followed this trend with a better distribution causing lower voidage yet higher permeability. In essence the results show that even though the permeability increases as the voidage increases within a given goal preparation a lower or similar voidage in another coal preparation will not necessarily produce the same result. It appeared that

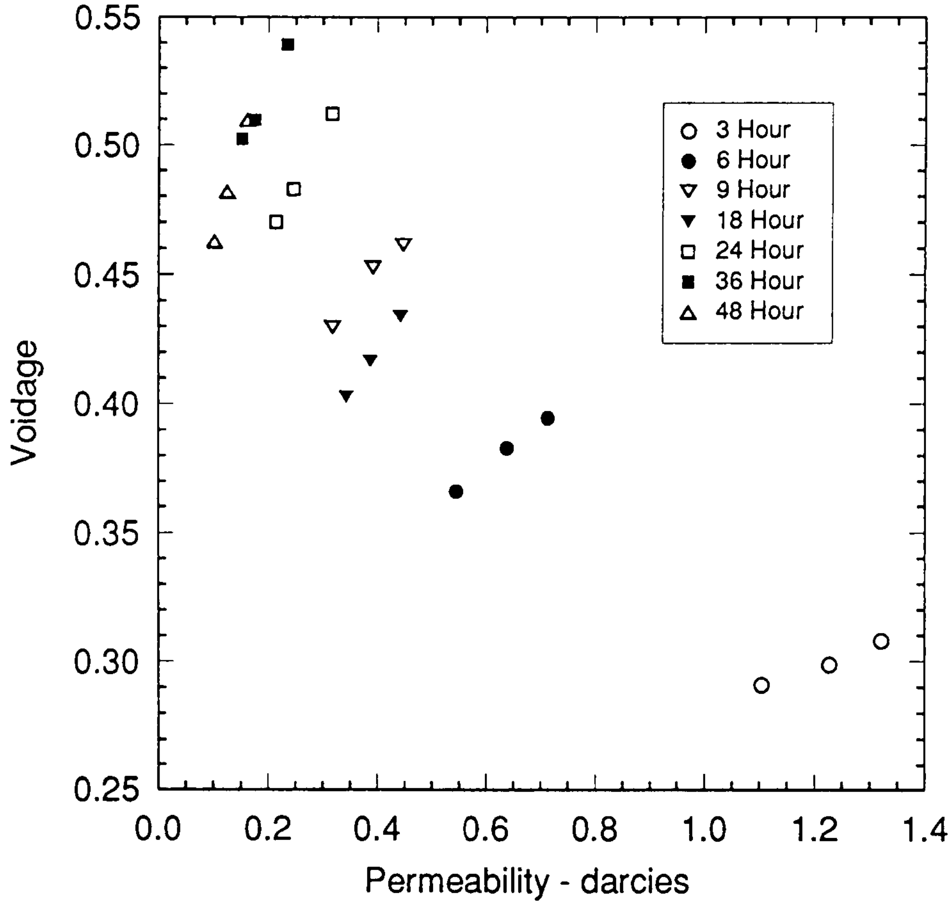

Figure 22. Summary of Eastern Coal Voidage vs. Permeability

as the particle size (MMD) decreased the actual voidage increased while the effective voidage or possible flow area through the coal decreased. Stated otherwise, the gas flow did not see the same voidage as was measured by the voidage calculations. From the consistency in the data showing this trend and experience in actual flow situations with smaller particles this is a logical explanation and therefore merits some further investigation.

Other recommendations for the improvement of this investigation include a better system of measuring column height by some positive stop measuring device, in which an average can be taken over the coal surface. Also other techniques could be used to vary the voidage such as compaction with a liquid for lower voidage or fluidization for higher voidage.

The results of this experiment, especially permeability, were reliable and accurate as expected. The relationship of particle size and particle size distribution with porosity were as anticipated. The relationship of porosity to permeability was as expected in like preparation coals. Even though the overall relationship of permeability with porosity over a range of coal preparation was not as anticipated this study should be a good baseline point from which to further investigate the gas-solid interaction in dense-phase flow of pulverized coal.

BIBLIOGRAPHY

BIBLIOGRAPHY

Arnold, B. J. "Review of Research on Coal-Handling Characteristics," EPRI Report GS-6677 prepared by Kaiser Engineering, Inc., 1990.

Cadle, Richard D. Particle Size. New York: Reinhold Publishing Company, 1962.

Carman, P. C. Flow of Gases Through Porous Media. New York: Academic Press, 1956.

Collins, R. E. Flow of Fluids Through Porous Media. New York: Reinhold Publishing Company, 1961.

Davidson, J. F. and D. Harrison. Fluidization. New York: Academic Press, 1971.

Everett, D. H. and F. S. Stone. The Structure and Properties of Porous Materials. New York: Academic Press, 1958.

Foote, J. P. Private conversation. The University of Tennessee Space Institute, 1989.

Furley, R., and F. H. H. Valentin. "Effect of Particle Size Upon the Strength of Powder," Powder Technology, 1 (1967), 344-54.

Hawk, M. C. "Bulk Materials Handling," Technical Report prepared by Office of Special Projects and Services, the University of Pittsburgh, n.d.

Harr, M. E. Mechanics of Particulate Media. New York: McGraw-Hill Book Company, 1978.

Hogg, P., *et. al.* "Fundamental Studies of Bulk Flow of Fine Coal," Quarterly Report DOE/PC/70805-7 prepared for the U.S. Department of Energy by Pennsylvania State University, 1986.

Jenike, A. W. *et. al.* "Flow Properties of Bulk Solids," Proceedings of the American Society of Testing and Materials, 60 (1960), 1168-81.

Johanson, J. R. "Know Your Material - How to Predict and Use the Properties of Bulk Solids," Chemical Engineering, 85 (1978), 9-17.

Klinzing, G. E. Gas Transport. New York: McGraw-Hill Book Company, 1981.

Konrad, K. "Dense-Phase Pneumatic Conveying: A Review," Powder Technology, 44 (1986), 1-35.

Kuni, D. and Octave Levenspiel. Fluidization Engineering. Malbar, Florida: Robert E. Krieger Publishing Company, Inc., 1987.

Larson, D. G. "Derivation of Generalized Darcy Equations for Creeping Flow in Porous Media," Ind. Engineering Chem. Fundamentals, 20 (1981), 132-37.

Ling, S. J. "Dense-Phase Pneumatic Conveying of Fine Coal." PhD Dissertation, University of Bradford, 1988.

Lowell, S. Introduction to Powder Surface Area. New York: John Wiley and Sons, 1975.

Lowry, W. E. "Pulverized Coal in Dense Flow," EPRI Report AP-5214 prepared by Montana States Energy, 1987.

Marchello, J. M. and Albert Gomezplata. Gas-Solids Handling in the Process Industries. New York: Marcel Dekker, 1978.

Schmidt, H. J. "Dense Phase Transport," UTSI Research Brief, 1984.

Schmidt, H. J. and J. N. Chapman. "Investigation of Moisture Content and Particle Size Effects on the Permeability of Pulverized Coal," Technical Proposal #91-21 prepared in response to Department of Energy/Pittsburgh Energy Technology Center (DOE/PETC) Solicitation #DE-P522-91PC912822 by the University of Tennessee Space Institute, 1991.

Schmidt, H. J. and J. N. Chapman. "The Influence of Feedstock Permeability on Dense prepared Phase Transport of Pulverized Coal Fuels," Technical Proposal #90-16 prepared in response to DOE/PETC Solicitation #DE-P522-90PC90282 by the University of Tennessee Space Institute, 1990.

Sprause, K. M. and M. D. Schuman. "Dense-Phase Feeding of Pulverized Coal in Uniform Plug Flow," AICHE Journal. 29 (1983), 1000-6.

White, F. M. Viscous Fluid Flow. New York: McGraw-Hill Book Company, 1974.

Zenz, F. A. and D. F. Othmer. Fluidization and Particle-Fluid Systems. New York: Reinhold Publishing Company, 1960.

VITA

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