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FINAL REPORT

COAL-SAND ATTRITION SYSTEM AND ITS IMPORTANCE
IN FINE COAL CLEANING

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ABSTRACT

It is known that ultra-fine coals are prerequisite for the deep cleaning of most U.S. coal seams if environmental pollution arising from the use of such coals is to be minimized. Therefore, the production of finely liberated coal particles in conjunction with reduced heavy metal contaminants at low costs is desirable, if not mandatory. The liberation of intimately disseminated impurities from the coal matrix therefore, demands that the material be ground to a high degree of fineness. Similarly, some technologies for coal utilization require superfine particles (i.e., sizes less than ten microns). This implies additional costs for coal preparation plants due to the high energy and media costs associated with fine grinding operations. Besides, there are problems such as severe product contaminations due to media wear and impairment of the quality of coal. Hence, proper choice of grinding media type is important from the viewpoints of cost reduction and product quality.

The use of natural quartz sand as grinding media in the comminution of industrial minerals in stirred ball mills has been indicated. The advantages of natural sand compared to steel media include low specific energy inputs, elimination of heavy metal contaminants and low media costs.

In this work, the effect of rotor speed, solids concentration and feed size are studied on four coals in conjunction with silica sand and steel shot. The coals chosen were: Pocahontas #3, Pittsburgh #8, Illinois #6 and Black Creek, thus representing a range of hardgrove grindability index. The results obtained are used to evaluate the suitability of silica sands as an alternative grinding media for coal. Coal-sand and coal-steel systems are compared in terms of specific energy consumption, product fineness, media/wear contamination, proximate analysis and calorific values, liberation spectrum and particle shape characteristics. Attempts have been made to optimize the process parameters of the two systems.

The fracture mechanics data (stress, strain and Poisson ratio) indicate that though Pocahontas #3 coal is the softest (i.e. easy to grind), it equires substantial fracturing stress possibly because of its clay constituents.

It was interesting to note that sand media produced a more spherical product shape than steel media for all coals studied. Media type appeared to have no significant effect on the liberation spectra except for the Pittsburgh #8 coal which exhibited the improved liberation of carbonaceous material with steel media.

In general cleaner flotation concentrate was obtained from coals when they were ground with sand media. The zeta potential of coals was found to be different and lower when they were ground with sand.

I. INTRODUCTION

A. Fine Grinding as an Important Step in Coal Beneficiation

Coal is a heterogeneous material which consists of a large number of impurities. The impurities affect the properties of coal and consequently, the utilization potentials. The presence of some mineral matter and particularly sulfur, adversely affect the use of such coals in combustion, metallurgical processes, synthetic fuel and chemical production, and as substitutes in diesel engines. The fact that the impurities are often finely dispersed in the coal structure or matrix implies that an extensive grinding is required for a significant/substantial liberation and consequently for a better separation to be achieved. Fine grinding is an important facet in the development of advanced coal cleaning technologies aimed at producing super-clean and ultra-clean coals. The availability and use of such coals would help to mitigate the high operating costs of existing industrial and electric utility boilers, open potential new applications for coal, and makes it fairly easy for users to meet the increasingly stringent environmental regulations.

With the advent of the 1970 Clean Air Act and recent problems associated with acid rain there has been an ever increasing interest in the production of fine coal particles primarily from stringent environmental regulations about the emission of NO_x and SO_x . The ramification of is that most coals must be subjected to a high degree of size reduction in order to meet the required specification. Since the impurities associated are usually finely disseminated in the coal matrix, it is necessary to reduce the particle size substantially in order to liberate the mineral matter and subsequently effect their separation in downstream processes. It has been reported that sufficient liberation is obtained mostly in particle sizes finer than 400 mesh (37 microns). At this size, most of the mineral matter is either liberated or forms a part of the exposed particle surface. It has been reported that a substantial liberation is achieved in this size range to ensure deep cleaning of most U.S. coals, thus making a large number of U.S. coal seams suitable as potential fuel stocks (Adel et. al., 1989, Ralph et. al., 1989, Borzone and Oder, 1992).

B. Requirements for Alternate Grinding Methods

Commercial production of such fine coal particles is at present non-existent, but a switch is anticipated with further advancements in the technologies involved. Stirred ball milling is a proven technology used in the paint and industrial minerals industry to produce ultrafine particles. The

mill can easily be adopted for grinding coal as have been demonstrated on laboratory scale. However, grinding particles to ultrafine sizes does pose a serious economic question due to the associated high electrical power and grinding costs involved. The primary factors responsible for the high cost of grinding are: (1) the high cost of steel grinding media, (2) the high cost of energy in grinding, (3) the high wear rate of the grinding media, (4) the high capital cost of the mill. Couch (1991) has reported that milling cost increases sharply when grinding to particle sizes finer than 50 μm and that grinding cost represents a significant fraction of the total costs of advanced coal cleaning.

This problem has been known for quite sometime and numerous attempts have been made to address the issue both by way of circuit design and the development of new grinding devices (Rogers and Austin, 1989). While a number of grinding mills can be used for the purpose of fine size reduction having different configuration of the grinding chamber in order to reduce the energy consumption (Union-process, Netzsch, Draiswerke, Pitt, Matter-AG and others, some are obviously more efficient than others for a specific size range. Therefore, a careful choice of comminution devices (having high grinding rates or high unit capacity per capital outlay) is essential in order to ensure that the operation is economically viable. But research efforts have not been undertaken to develop more energy efficient size reduction processes by finding alternate media types (Rogers and Austin, 1989). Principally, coal grinding research in any of these mills is being currently conducted using steel balls as a grinding media. The obvious disadvantages of using steel media are high replacement cost, contamination of coal through media wear, greater degree of coal oxidation due to higher slurry temperature and greater degree of noise pollution due to the higher sound level.

The characteristic fine size grinding media required in most ultrafine grinding operations while being advantageous in terms of size reduction, does have a negative impact in terms of costs. It is known that grinding media cost increases rapidly with decreasing size. In fact, Borzone and Oder (1992) have reported that the variation in the price of a one-half kgs of 4.8 mm to 1.5 mm chrome alloy steel ball compared with an equivalent amount of 7.9 mm ball ranges for 440 % to 1550 %. Hence, grinding media is a critical factor in the economic viability of the application of stirred ball milling particularly in the production of relatively low value added materials. Besides the use of relatively coarse size grinding media as a possible remedy, the other alternative is to employ fairly cheap media types which would not impair the mill performance.

C: Objective and Scope of the Research

The main objective of this research was to make an advancement of the concept of using a:

inexpensive and effective grinding media (i.e. fracturing silica sand) as a substitute for steel media in the coal grinding process. The proposed research was based on the laboratory batch tests as well as bench scale continuous tests, which indicated that when hard fracturing silica sand was substituted for steel media then, not only the disadvantages as mentioned above are taken care but additionally superior energy savings on the order of 50% and more could be realized.

Within this general objective, specific research objectives were:

1. To validate the preliminary observations made on coals of varying properties.
2. To establish the range of optimum operating conditions of this novel grinding process in a batch mode and continuous mode.
3. To generate fundamental information on breakage of coal particles based on the principles of fracture mechanics.
4. To characterize particle shape, and the liberation spectrum of ground product coal for coal-sand and coal-steel attrition systems for the purpose of its subsequent usage in physical coal cleaning and coal slurry applications.

The scientific rationale which follows, presents the experimental evidence, describes the theoretical basis of the research, and defines the sequential series of tasks which were undertaken to achieve the stated objectives.

D. Scientific Rationale and Preliminary Tests

An attrition grinding process developed at the U.S. Bureau of Mines for ultrafine clay grinding has been commercially adopted by the clay industry (Feld, et al; 1960, Stanczyk and Feld, 1963, 1965, 1968, 1973; Davis et al; 1973). This process has also shown to be effective for other industrial minerals (Stanczyk and Feld, 1972). There are two novel aspects of this process. The first aspect is the use of silica sand in the size range of 8 mesh to 65 mesh as a grinding media, the second aspect is the design of the attritor (rotor-stator cage design). The prime thrust in development of this novel process was to avoid contamination. However, it turned out that this process demonstrated a good material handling capacity, high grinding rates and moderate power consumption. In the U.S. Bureau of Mines studies, relatively fine silica sand (14 mesh and smaller) was used for clay material of -44 microns. Their process was further successfully applied to industrial minerals of coarse size such as barite (-35 mesh), mica (-35 mesh), pyrophyllite (-38

Table 1. Experimental conditions and results for the batch attrition tests with Blue Creek Alabama coal -100 mesh feed (50 gm coal, 387cc water, grind time 5 min)

pt.	Media Charge gm	RPM	Dead Power watt	Average Power watt	Net Power watt	Net Specific Energy kwh/t	d _{50,f} micron	d _{50,p} micron
	(flintshot) 1272	1500	334.4	376.1	41.7	69.5	45	2.6
	(flintshot) 1272	2400	374.0	551.7	177.7	296.1	45	2.1
1)	(2mm chrome 3763 beads)	1500	334.4	734.0	399.6	666.0	45	3.9

Table 2. Coal contamination and media consumption data for expt. 10

Element	Feed Coal wt %	Micronized Coal wt %	% Increase Due to Grinding	lbs of Element Uptake T Coal	Media Consumption* lb/T
Cr	0.001	0.15	0.149	3.28	16.40
Ni	0.002	0.02	0.018	0.39	
Mn	0.005	0.044	0.039	0.86	
Cu	0.011	0.017	0.006	0.13	

* based upon high chromium - carbon steel beads having 20% chromium (ref: Sailors, 1990)

mesh), Talc (-35 mesh), marble (-35 mesh), fluorite (-65 mesh). In grinding of these industrial minerals a coarse sand size distribution (-8 mesh) was used.

A literature search revealed that no further attempt has been made to undertake ultrafine grinding of coal in attritor/stirred ball mills using silica sand. To test the feasibility of this approach, -100 mesh feed Alabama coal (Blue Creek seam) was ground in batch Denver attrition scrubber having no lining alternatively with steel balls and with silica sand (trade name #4 flintstone: -20 + 48 mesh monocrystalline quartz). Table 1 compares the energy (kwh/t) consumed in grinding with sand and steel media. For example, grinding with steel media resulted in a product median size of 3.9 microns with $E=666.0$ kwh/t energy input whereas the same coal feed was ground with sand to a median size of 2.1 microns with $E=296.1$ kwh/t. This clearly shows the energy savings of 56% when sand is used as the grinding media. The grinding efficiency achieved with sand as compared to that with steel balls can be further seen by their overall size distributions which are plotted in Figure 1.

With regard to coal contamination (Table 2), there was significant increase of almost 15% in chromium with steel media whereas it is clear that there is no contamination when sand is used as grinding media. With regard to media consumption, an estimate of 16.4 pound of steel media per ton of coal was calculated for experiment 10 (Table 2) whereas there was complete recovery of sand. Similar data, i.e. negligible consumption of sand was also observed in grinding clay and industrial minerals (Stanczyk and Feld; 1963, 72).

Another interesting observation made during these experiments revealed that the slurry temperature was only 27°C with sand whereas it was found to be 42°C with steel media. It is our belief that the higher temperature slurry not only promotes oxidation of the coal but also makes the process more energy inefficient. To supplement this observation, we performed BTU analysis on sand and steel media ground Blue Creek coal which showed values of 14,414 and 13,724 Btu/lb, respectively.

Very few attempts have been made to find a replacement for steel media. One study showing the comparison of steel and glass media for coal grinding in low speed attritor has been reported (Mankosa, Adel & Yoon, 1986). In this study, the comparison was made on the basis of equal specific energy input. The only variable which was manipulated was grinding time and all other operating variables were the same. They concluded that the glass media required a longer grinding time to achieve the same energy input as that of steel media. This was not surprising considering the density of glass media (2.659/cc) as compared to that of steel media (7.659/cc). What we believe is that, since glass beads is a lower density material, higher rotor speed is necessary to

Figure 1. Experimental product size distribution obtained for conditions listed in Table 1

Figure 2. Schematic representation of batch and continuous attrition grinding configuration along with a real time data acquisition system used for monitoring the power draft

achieve threshold kinetic energy for breakage of coal particles. Therefore, coal-glass media system should have been operated at a higher rotor speed and, correspondingly, grind time should have been varied to achieve targeted specific energy input.

To validate this observation, -100 mesh Black Creek coal was ground in Denver batch scrubber using equal size of steel and sand media (1.1mm steel beads and 12 x 20 mesh fracturing silica sand). It was interesting to note that coal-sand attrition system produced finer product coal size distribution when these two systems were compared on equal values of specific energy input. These results are shown in Table 3.

In the context of this preliminary work, it is important to mention the difference between glass and sand media: glass is an amorphous borosilicate material, whereas sand is a much harder monocrystalline quartz, and secondly, sand is highly hydrophilic in nature, whereas glass beads are like steel beads in this respect.

It is reported in the literature (Sepulveda, 1981) that linear breakage kinetics prevail in ultrafine stirred milling for coal and chalcopryite up to certain values, which depend on the device and grinding conditions, and beyond this value non-linear breakage mechanism prevails. We conducted preliminary batch experiment in batch attrition scrubber (see Figure 2) which was instrumented to measure power drawn during grinding. Figure 3 shows computer monitored power draft of batch attrition tests listed in Table 1. Preliminary batch grinding tests conducted on 150 x 200 mesh Blue Creek coal for 1 and 2 minutes time using 2mm steel media and 28 x 35 mesh silica sand indeed showed the linear breakage kinetics (see Figure 4). It was quite encouraging to note that the energy normalized specific rate of breakage $(\text{kwh/t})^{-1}$ of coal with silica sand was almost 2 times higher than that of steel media, as shown in this figure.

Another interesting observation made during these experiments showed the effect of sand particle size on the size distribution of coal. As shown in Figure 5 coal was more finely ground with natural sand, i.e. (20 x 48 mesh) and lower energy input (147 kwh/t) in comparison to 28 x 35 mesh sand at 150 kwh/t. Therefore, sand size distributions will be manipulated so as to achieve maximum fineness with minimum expenditure of specific energy input.

The batch tests conducted were used as a guide in determining the overall effectiveness of continuous grinding tests with respect to feed rate, % solids, sand loading, residence time and rotor speed. The preliminary continuous tests were conducted in a LME-4 Netzsch mill in Pin configuration. This mill was equipped with pressure, temperature and power transducers and connected with data acquisition system to measure instantaneous power draft of the mill during

Table 3. Experimental conditions and results for the batch attrition tests with Black Creek Alabama Coal -100 Mesh Feed (60gm wet coal, 1272gm fracturing silica sand [12x20 mesh], 3763gm 1.1mm steel beads) at equal values of specific energy input (.466 kwhr/kg)

t.	Water added cc	RPM	Net Power watt	Time minutes	Feed (microns)		Product (microns)	
					d ₉₀	d ₅₀	d ₉₀	d ₅₀
11	290*	2400	243.8	7.0	110.9	37.0	5.6	2.4
11	40	1200	317.0	5.3	110.9	37.0	9.1	3.1

Sand 1 expt. uses 250cc of water to completely wet the sand charge

Table 4. Experimental conditions and results for the LME-4 Netzsch Mill open-circuit test with Blue Creek Alabama coal -100 mesh feed at 36% solids by weight

	Volumetric Flowrate cc/min	RPM	Dead Power watt	Measured Power watt	Net Power watt	Net Specific Energy kwh/t	d _{50,f} micron	d _{50,p} micron
Sand	280	1400	1330.6	2130	799.4	118.64	22.7	2.7
	260	1500	1369.4	2600	1230.6	196.6	22.7	2.4
	250	1600	1431.4	3005	1573.6	261.6	22.7	2.3
Steel balls	320	1400	1330.6	4130	2799.4	363.5	22.7	3.7
	320	1500	1369.4	5050	3680.6	477.9	22.7	3.4
	320	1600	1431.4	5840	4408.6	572.5	22.7	3.3

Test (1,2,3) mill loading 85% by volume (20 x 30 mesh silica sand) = 3352 gm, void volume = 1265 cc

Test (4,5,6) mill loading 85% by volume (2mm steel balls) = 9916 gm, void volume = 1265 cc

Figure 3. Computer monitored power draft for batch attrition tests listed in Table 1

Figure 4. First order energy normalized disappearance plot obtained for monosize attrition grinding using sand and steel balls

Figure 5. Size distribution of coal obtained as a function of sand particle size used in batch attrition tests

Figure 6. Experimental product size distribution obtained for open-circuit continuous runs listed in Table 4

grinding studies. Figure 2 is a schematic representation of the computer monitored power measurements for LME-4 Netzsch mill. Preliminary continuous runs using a coarse foundry sand (20 x 30 mesh) and -100 mesh feed coal were made and these sand runs showed excellent results over grinding runs made with 2mm steel media. These results are shown in Table 4 and size distributions are plotted in Figure 6.

We again saw finer median size as well as overall finer size distributions obtained with 50% and higher energy savings using sand.

It has been well established that kinetics of grinding begins to be influenced by the very fine size consist of the mill (Sepulveda, 1981). This aspect is very important particularly for ultrafine grinding of coal using hard silica sand for two reasons:

1. Typically sand has finer and relatively wider particle size distribution, therefore, this system typically tends to produce more fines. This is clearly shown in figure 2 where Exp. 9 has a finer distribution than Exp. 10.
2. More zero size material (-1 micron) is also produced implying that attrition mechanism may be more important than fragmentation mechanism. This is evident by comparing -1 micron coal obtained in batch tests for Expt. 9 (sand) and 10 (steel balls) which is 21.7 and 16.0%, respectively. Also, compare similar results of Test (1,2,3) against Tests (4,5,6) plotted in Figure 6.

From the results of these preliminary experiments and available literature grinding data on industrial minerals, it was convincing that that fundamental studies on coal-sand attrition system was needed in order to develop more energy efficient and environmentally clean grinding systems. Some of the obvious advantages of this approach are as follows:

- 1) Reduced power consumption, i.e. specific energy input (kwh/t).
- 2) Improved product quality, i.e. no contamination of ground coal product from media wear such as Fe, Cr, Ni, Mn, etc.
- 3) No steel media wear.
- 4) Minimal heat generation and resultant lower coal oxidation.

- 5) Very low levels of sound is attained during grinding thus making process more energy efficient
- 6) Savings in manpower time (do not require media cleaning and inert atmosphere for storage, which on the other hand is a must for steel media).

II. EXPERIMENTAL

A. Materials

1. Coal samples

A drum of each Pittsburgh # 8 and Illinois # 6 coal seams samples were obtained from the Southern Electric International Center of Alabama Power Company at Wilsonville. The Black Creek sample was obtained from the Drummond coal company at Jasper, Alabama. The Pocahontas # 3 coal seam sample was obtained from Virginia. These coal samples were chosen after consultation with the technical project officer, Mr. Otis Mills, to cover a range of properties such as hardness, sulfur content, mineral matter distribution and keeping in view the interest of DOE in cleaning these coals.

2. Sample Preparation

About 30 kg. of each coal types were taken from the bulk samples and dried at 40C for about 3 days. The partially dried material was then reduced in stages down to required size. The Black Creek and Pittsburgh coal samples being very coarse were first subjected to crushing in a jaw crusher. Thereafter, the materials were screened at 6 mesh and the oversize were further ground in a roll mill until all the particles could pass through the 6 mesh screen. The -6 mesh materials were each thoroughly mixed and subsequently split down to about 10 kg. using a riffle. The 10 Kg lots were used in determining the bond indices.

A 2 kg. of 14X28 mesh material was prepared from the other fraction for the Hardgrove index determination, while the remaining materials were further reduced in steps down to 50 mesh size. The - 50 mesh material was subsequently used to prepare the narrosized fractions required for the batch optimization tests.

In order to preserve the properties of the coals, a sample preparation strategy was adopted whereby the respective coal samples were prepared in small batches to be used for specific tasks. The different size fractions prepared were placed in plastic bags which were further stored in tightly sealed containers.

B. Methods

1. Bond Grindability Determination

The -6 mesh materials prepared were used in these tests. The method as suggested by Hazen Company was used. In this method a certain amount of -6 mesh coal was slowly poured in a 2000 ml. graduated cylinder while tapping to settle and compact the material, until 700 ml mark is reached. The material was then weighed and used in the grinding test carried out in the Bond Mill.

A grinding media charge of about 20 kg. consisting of the following sizes, numbers, and weights, were employed:

<u>Size(mm)</u>	<u>Numer of Balls</u>	<u>Weight (kg)</u>
39.9	37	9.82
31.8	44	5.82
24.1	32	2.24
18.3	25	0.86
12.7	59	1.40

		20.14

The targeted size was arbitrarily chosen as 65 mesh because of the ease with which the ground material could be sieved at this size. It was assumed that at equilibrium operating conditions, a circulating load of 250% and a 100% -65 mesh product are desired. The number of revolutions the mill must be operated to achieve the 250% circulating load was then determined by trial and error. after grinding, the material was sieved in three batches, each for a duration of 10 minutes in order to ensure an almost complete removal of the fine particles. In this method, a part of the initial starting material was used (until the desired circulating load is obtained) and the starting weight mass is maintained by the addition of an equivalent amount of fresh feed to replace the fines produced.

This cycle was repeated until a constant circulating load was obtained. In this way, the amount of material produced per revolution required in the work index equation was determined from the average value of repeated runs. The feed and product size distributions were obtained by sieving both materials for a duration of 15 minutes and the 80% passing sizes were determined from subsequent plots of the data.

2. Hardgrove Grindability Determination

The coal samples of 14X28 mesh size were prepared and sent to R & D Center of Drummond Coal Company because our Institute did not have the grindability tester. The standard ASTM procedure was followed

3. Sample Characterization

The -60 mesh coal material and the monodispersed feeds prepared for batch grinding tests prepared from the coal samples were subjected to ultimate and proximate analyses, calorific value measurements, forms of sulfur, and chemical analyses for calcium, chromium, copper, iron, magnesium, manganese, and nickel. These analyses were done according to ASTM procedures. The ground coal products were also characterized in the same way.

4. Scanning Electron Microscopy -Image Analysis

Twelve (12) samples consisting of four 200X270 mesh raw feed coal samples and eight 200X270 mesh ground product samples were thoroughly screened to remove -270 mesh fines. Following the wet screening, the 200X270 mesh material was mounted in briquettes consisting of melted Carnauba wax and polyethylene (1:1 weight ratio). These briquettes were then sectioned and the sections remounted to eliminate gravitational and orientation effects. Finally, the briquettes were sputter-coated with gold and analyzed using a Cambridge Stereoscan 150 SEM in conjunction with a Kontron SEM-IPS image analysis system.

Three phases, consisting of mineral matter, pyrite and carbonaceous material, were identified from the back scattered electron image, and the images were analyzed to determine the area fraction of each phase present in a given particle. Weight % for each phase were obtained by assuming area fraction was equivalent to volume fraction and by using specific gravities for carbonaceous material, mineral matter and pyrite of 1.3, 2.65, 5.0 to convert the volume fraction to mass fraction data. At the same time, the circular shape factor was given by:

$$(4 \pi \text{ area}) / (\text{perimeter}^2)$$

was determined for each particle. In general, approximately 1500 particles were analyzed for each

sample.

5. Batch Grinding Tests

The coal sample was dried at a low temperature for two days. Then it was crushed in stages using a jaw crusher and simultaneously screened with a 50 mesh sieve. The resulting coarse fraction was further ground in a roller mill to a minus 50 mesh size. Thereafter, the monodispersed feed sizes required were prepared from the minus 50 mesh material. The grinding tests were carried out using a modified Denver flotation machine equipped with a grinding chamber and rotor configuration shown in Figure 7.

The chamber has a net volume of 230 ml and about 60 % of the volume was filled with both grinding media and slurry during each test in order to minimize spillage. Silica sand and steel shots of about 1mm size were used as grinding media. The volumetric filling was kept constant for the two media types. Batch grinding method was employed. Once the rotor was set in place, the required amount of grinding media was introduced followed by coal and water prior to the commencement of grinding. The time duration used for each test was fixed at a predetermined value. The grinding media were separated by screening the slurry on a 60 mesh screen. The particle size distribution of the undersize was analysed using Cilas granulometre 715. The power draw of each test was measured using the DAS-16F data acquisition system.

6. Continuous Grinding Tests

The continuous grinding tests were not made in LME-4 Netzsch Mill because the grinding chamber did not have lining as required in sand grinding runs to avoid steel wear. Therefore, a small grinding chamber similar to that used in the batch tests but fitted with inlet and discharge openings was adopted. A variable speed Masterflex peristaltic pump was placed between the mixing tank, water tank and the grinding chamber inlet port and connected by a system of tubing, as shown in Figure 8. The small size of the grinding chamber necessitated the use of a relatively low feed rate in order to keep the residence time of the particles in the mill at a reasonable level. Evidently, this was not enough to ensure that the desired very fine product can be obtained. Hence slurries had to be passed through the mill a number of times, thereby simulating a grinding circuit consisting of a number of mills in series. Depending on the hardness of the coal, between 3 to 4 passes were sufficient to obtain very fine products. The harder the coal, the higher the number of passes required. This is of course influenced by such factors as the initial feed particle size, pulp density, feed rate and stirring speed.

Fig. 7 Schematic Diagram of the MRI Batch Attrition Scrubber with Polyurethane Lining for Conducting Coal - Sand Attrition Tests. All Dimensions Shown Are in Inches.

Fig. 8

Schematic Representation of the Continuous Grinding Test System

The fact that no media retaining device was employed in the discharge port placed some limitations on these runs. The decision to use an open discharge port was reached as severe clogging problems prevented the use of sieve as a retaining device. Even without the retaining device, the grinding operation has to be carried out in such a manner that most of the media remain in the grinding chamber for it to be effective. This was achieved by exploiting gravitational force or specific gravity difference to effect the separation of coal slurry from the media inside the grinding chamber. The implication is that the mill capacity has to be compromised as less than optimal levels of such factors as feed particle size, feed flow rate and initial solids concentration have to be employed.

With the above restrictions in mind, we set out to explore the range in which the continuous grinding circuit can be used to produce products consisting of very fine particles. In these tests, two polydispersed feed with a size designation of minus 50 mesh and minus 100 mesh were chosen as well as initial solids concentration in the range of 20 to 40 weight percent. The term initial solids concentration was used to denote the starting pulp density in the mixing tank. The starting solids concentration is emphasized because the operating procedure adopted results in a slight dilution of the commencement of grinding.

The procedure involved measuring the desired amount of dry coal and water and mixing in a stirred tank to give the pulp density of interest. Then the stirring mechanism was set in place, the required amount of grinding media measured (which for silica sand is chosen as 250 g) and placed in the mill. Thereafter the mill cover was locked, the water valve was opened and the pump was switched on. Then the mill cover and tubes were checked for leakage and the pump speed was adjusted. After the check up, the grinding mill motor was switched on, the water valve was closed while the slurry valve was opened and further adjustments were made on the the pump speed. This procedure appeared to be essential for a smooth running of the continuous grinding system. However, when a small volume of slurry was used, a significant dilution might result.

For the four coals employed in this work, it was not possible to effectively grind the minus 50 mesh feed even at the lowest solids concentration range tried. The reason for this was the low feed rate which made it impossible to obtain a uniform flow as the coarse particles in the feed tend to settle down and form sediment in either the tubing system or the grinding chamber. Besides, only moderate levels of solids concentration could be employed . Attempts to increase the flow rate resulted in the grinding media being taken out of the mill together with the slurry. As a result of these limitations posed by the instrument, further tests were restricted to using minus 100 mesh feed size and moderate levels of feed rate and pulp density. The media wear was determined from the difference in the mass of the media after grinding.

7. Fracture Mechanics Tests

In this tests, four monodispersed and one polydispersed samples prepared from each of the four coal types were used. The so-called uniaxial testing machine manufactured by Tinius Olsen was used to apply the required load on the sample which was placed in a cell as shown in the Figure 9 made for this purpose.

Preliminary test runs were first made to determine both the amount of sample required to obtain a cylindrical cake of about 4 inches in height and a load which would yield a cake of adequate strength.

It was decided from the trial data to use 240 grams from each of the dry coal samples. In order to obtain a cake following the application of load, an amount of water varying between 34 to 80 ml was used to increase the moisture content of the sample. The variation in the amount of water required is due to the degree of fineness of the particles which make up the samples. A constant pressure of about 12,700 psi was chosen for the test and applied for a duration of one hour. Cylindrical cakes having a diameter of 2 inches and a height varying between 4 to $4\frac{1}{2}$ inches were obtained depending on the coal hardness and initial particle size. Additional samples were made on two other lower pressure values.

The wet cylindrical cores were weighed and allowed to dry in air for a number of days before being subjected to further uniaxial compression tests. In these tests series, small increments of load were applied on each of the core and the strain release was measured using a dual-sensor strain transducer (supplied by the Measurement Technology Inc.), connected to two strain indicators model P 3500 made by the Measurement Group. The vertical and horizontal strains were measured in this manner when a core was subjected to stress.

8. Zeta Potential Tests

The zeta potential measurements of the raw feed coal and ground coal products were carried out using Lazer Zee Meter Model 501. The coal material used was -325 mesh. The pH of the solution was adjusted using sodium hydroxide and sulfuric acid. For each coal 0.8 gram coal was suspended in 1000 ml of distilled water and the ionic strength of the solution was maintained at .005M KCl.

9. Mechanical Flotation Tests

Flotation response of ground coal products was measured by the Denver flotation tests. These tests were conducted in a 2 liter Denver Cell at 2300 rpm. The flotation tests were done at a pulp density of 2.5 % solids by weight. For some coals and in some of the tests, MIBC and kerosene were added as frother and collector respectively.

III. RESULTS AND DISCUSSION

A. Comparison of Grindabilities

The Bond and Hardgrove indices of the coal are listed in Table 5.

Table 5. Bond and Hardgrove Indices of the four coal seams

Coal Seam	d ₈₀ (microns)		Indices	
	Feed	Product	Bond (Kwh/t)	Hardgrove
Black Creek	2400	166.5	17.46	57
Illinois #6	2500	162	13.51	55
Pittsburgh #8	2184	168	13.37	61
Pocahontas #3	2136	169.5	8.05	93

It is clear from the data of Table 5 that the Bond grindabilities determined are consistent with the normal published qualitative range of hardness. The reason for the selection of these coals was based on the HGI values in that it was conceived that the Black creek coal is the hardest, Pocahontas #3 is the softest and both Illinois #6 and Pittsburgh #8 coals have the similar hardness. The Bond indices prove this trend, however, the actual HGI data obtained by the Drummond coal R & D Center showed the Black Creek coal was 10 units off from the previously reported literature value (47) and Pocahontas # 3 was off by 3 units. The Illinois and Pittsburgh coals results were consistent with what is reported in the literature. Besides, the pattern displayed by the results differ from that obtained by Bond method since the Black Creek coal seems to be softer than than Illinois # 6 coal. It was not quite obvious whether this discrepancy was due to either experimental or sampling error.

B Attrition Cell Design

The grinding cell to be used for the batch tests was designed by using the principles of geometric similarity to scale down large stirred mills. The cell and stirring mechanism were made of stainless steel and lined with polyurethane. A schematic of the cell is shown in Figure 7.

C. Coal Characterization

Six different size fractions of each raw coal were analyzed in terms of Proximate Analysis, Ultimate Analysis and forms of sulfur. Additionally, the coal ash was analyzed for different elements (Ca, Cr, Cu, Fe, Mg, Mn and Ni) in view of estimating the media contamination before and after the grinding. Similar analysis was also carried out for the ground products. The coal analysis data of feed coals is listed in Tables 6-9. It is clear from the data that the analysis for any one coal does not differ significantly from size to size. The analysis of Black Creek coal showed that in-fact it was a lower ash and sulfur coal compared to other coals. The analysis of coal ash resulting from the Pocahontas # 3 coal showed that the Ca and Mg content was the highest showing the presence of excessive clay minerals. This was independently confirmed by the image analysis of feed coal samples as reported in the next section of this report.

D. Preliminary Batch Grinding Tests

Black Creek coal sample obtained from the Drummond Coal Company at Jasper, Alabama was used in these preliminary tests. The sample was crushed in stages and screened using a 50 mesh sieve. The required monodispersed feeds were then prepared from the minus 50 mesh material.

The grinding tests were carried out using a modified Denver flotation machine equipped with a grinding chamber and rotor configuration shown in Figure 7. The chamber had a net volume of 230 ml and about 60 % of the volume was filled with both grinding media and slurry during each test in order to minimize spillage. Silica sand and steel shots of about 1mm size were used as grinding media. The volumetric filling was kept constant for the two media types. Batch grinding method was employed. Once the rotor was set in place, the required amount of grinding media was introduced followed by coal and water prior to the commencement of grinding. The time duration used for each test was fixed at 8 minutes. The grinding media were separated by screening the slurry at the end of each test. The particle size distribution of the products were analysed using Cilas granulometre 715. Composite factorial design (Box, 1954), was used to study the effect of rotor speed, solid concentration and feed size on the grinding performance of the two media types. The levels of the factors used in the experiments are given in Table 10. The standardized variables X1, X2 and X3 are expressed in terms of the natural variables as follows:

$$X1 = \frac{X_{RS} - 1900}{500}, \quad X2 = \frac{X_{CC} - 30}{10}, \quad X3 = \frac{X_{FS} - 150}{50} \quad (1)$$

Table 6. Pocahantas #3 Coal Analysis

	<u>Mesh Size</u>					
	- 60	50 x 60	60 x 100	100 x 150	150 x 200	200 x 270
<u>Proximate Analysis (wt %)</u>						
Moisture	1.40	1.05	1.09	1.12	1.10	1.17
Volatile Matter	17.80	17.65	17.58	18.10	17.64	17.96
Fixed Carbon	74.76	74.21	74.64	74.51	75.28	74.52
Ash	6.02	7.09	6.69	6.27	5.98	6.35
<u>Ultimate Analysis (wt %)</u>						
Carbon	84.64	84.46	84.31	85.06	85.01	84.56
Oxygen (by diff)	3.66	1.95	2.44	2.01	2.37	2.45
Hydrogen	4.50	4.38	4.46	4.48	4.47	4.50
Nitrogen	1.23	1.20	1.17	1.20	1.20	1.19
Total Sulphur	0.95	0.92	0.93	0.98	0.97	0.95
Calorific Value (Btu/lb) (dry basis)	14,796	14,655	16,715	14,813	14,863	14,725
<u>Forms of Sulphur (wt %)</u>						
Pyritic	0.30	0.32	0.32	0.31	0.30	0.29
Organic	0.46	0.50	0.49	0.53	0.50	0.46
Sulphate	0.19	0.10	0.12	0.14	0.17	0.20
<u>Analysis of Coal Ash (wt %)</u>						
Calcium	0.05	0.05	0.04	0.04	0.05	0.07
Chromium	0.001	0.001	0.001	0.001	0.001	0.001
Copper	0.002	0.002	0.003	0.003	0.002	0.003
Iron	0.53	0.64	0.55	0.53	0.61	0.56
Magnesium	0.07	0.08	0.08	0.07	0.07	0.09
Manganese	0.002	0.002	0.002	0.001	0.001	0.002
Nickel	0.003	0.003	0.003	0.003	0.000	0.003

Table 7. Black Creek Coal Analysis

	Mesh Size					
	-60	50X60	60X100	100X150	150X200	200X270
Proximate Analysis (wt%)						
Moisture	2.55	2.21	2.38	2.39	2.48	2.39
Volatile Matter	30.42	32.94	32.32	31.60	30.44	29.05
Fixed Carbon	60.96	60.08	60.88	61.24	61.48	61.63
Ash	6.07	4.77	4.42	4.77	5.60	6.93
Ultimate Analysis (wt%)						
Carbon	77.61	79.46	79.65	79.11	78.04	76.93
Oxygen (by diff)	14.74	12.61	12.44	13.09	14.3	15.71
Hydrogen	5.22	5.54	5.45	5.39	5.27	5.10
Nitrogen	1.68	1.67	1.74	1.70	1.68	1.52
Total Sulphur	0.75	0.72	0.72	0.71	0.71	0.74
Heating value (Btu/lb)	13,649	14,258	14,469	14,088	14,024	13,656
Forms of Sulphur (wt%)						
Pyritic	0.10	0.07	0.06	0.07	0.10	0.14
Organic	0.52	0.57	0.58	0.56	0.51	0.46
Sulphate	0.13	0.08	0.08	0.08	0.10	0.14
Analysis of Coal Ash (wt%)						
Calcium	0.002	0.002	0.003	0.002	0.002	0.002
Chromium	0.001	0.001	0.001	0.001	0.001	0.001
Copper	0.002	0.002	0.002	0.002	0.002	0.003
Iron	0.265	0.183	0.192	0.220	0.345	0.306
Magnesium	0.030	0.025	0.030	0.032	0.038	0.033
Manganese	0.001	0.001	0.000	0.001	0.001	0.001
Nickel	0.003	0.003	0.002	0.002	0.003	0.003

Table 8. Pittsburgh #8 Coal Analysis

	Mesh Size					
	-60	50X60	60X100	100X150	150X200	200X270
Proximate Analysis (wt%)						
Moisture	2.51	2.32	2.36	2.49	2.49	2.67
Volatile Matter	37.64	37.87	37.46	37.47	37.18	36.53
Fixed Carbon	50.78	50.47	50.92	50.87	51.36	51.61
Ash	9.07	9.34	9.26	9.17	8.97	9.19
Ultimate Analysis (wt%)						
Carbon	71.82	62.25	71.78	71.55	70.93	70.49
Oxygen (by diff)	17.34	17.23	17.38	18.01	18.05	18.76
Hydrogen	5.19	5.25	5.31	5.29	5.24	5.21
Nitrogen	1.32	1.35	1.36	1.28	1.39	1.31
Total Sulphur	4.33	3.92	4.17	3.87	4.39	4.23
Calorific value (Btu/lb)	13,145	13,133	12,995	12,398	13,136	13,036
Forms of Sulphur (wt%)						
Pyritic	1.63	1.50	1.58	1.71	1.79	1.51
Organic	1.99	1.78	1.89	1.43	1.78	1.53
Sulphate	0.71	0.64	0.70	0.73	0.82	1.19
Analysis of Coal Ash (wt%)						
Calcium	0.006	0.005	0.004	0.005	0.006	0.008
Chromium	0.002	0.002	0.002	0.002	0.002	0.002
Copper	0.001	0.001	0.001	0.001	0.001	0.001
Iron	2.061	1.876	1.999	2.175	2.226	1.975
Magnesium	0.035	0.041	0.035	0.033	0.035	0.040
Manganese	0.002	0.002	0.002	0.002	0.002	0.002
Nickel	0.002	0.003	0.002	0.003	0.003	0.003

Table 9. Illinois #6 Coal Analysis

	Mesh Size					
	-60	50X60	60X100	100X150	150X200	200X270
Proximate Analysis (wt%)						
Moisture	9.08	8.18	8.54	8.78	8.82	8.59
Volatile Matter	35.10	35.48	35.88	35.02	35.10	34.96
Fixed Carbon	46.74	45.36	46.12	46.99	46.78	46.48
Ash	9.08	10.98	9.46	9.21	9.30	9.99
Ultimate Analysis (wt%)						
Carbon						
Oxygen (by diff)	63.98	63.36	64.16	64.07	64.19	63.16
Hydrogen	26.19	26.79	26.10	26.15	26.08	27.25
Nitrogen	5.41	5.36	5.48	5.48	5.47	5.37
Total Sulphur	1.31	1.28	1.24	1.28	1.29	1.26
Calorific value (Btu/lb)	3.11	3.21	3.02	3.02	2.97	2.96
	11,682	11,587	11,628	11,703	11,491	11,699
Forms of Sulphur (wt%)						
Pyritic	0.76	0.94	0.81	0.81	0.82	0.78
Organic	2.01	1.69	1.73	1.78	1.71	1.69
Sulphate	0.34	0.58	0.48	0.43	0.44	0.49
Analysis of Coal Ash (wt%)						
Calcium	0.016	0.153	0.061	0.029	0.030	0.039
Chromium	0.002	0.002	0.002	0.002	0.002	0.002
Copper	0.001	0.002	0.002	0.001	0.001	0.002
Iron	1.190	1.350	1.325	1.275	1.252	1.230
Magnesium	0.063	0.070	0.065	0.060	0.067	0.073
Manganese	0.003	0.004	0.004	0.003	0.003	0.004
Nickel	0.008	0.004	0.002	0.004	0.002	0.005

Table 10 Experimental Factors and Levels

Factors	Levels				
	-2	-1	0	1	2
X1: Rotor Speed (rpm)	900	1400	1900	2400	2900
X2: Coal Concentration (wt,%)	10	20	30	40	50
X3: Feed Size (mesh)	200 x 270	150 x 200	100 x 150	60 x 100	50 x 60

The design consisted of sixteen points in coded variables. The coded factors and measured response (in this case the median size of the ground coal) are listed in Table 11.

Statistical and preliminary Analysis

A polynomial equation was fitted to the data given in Table 11 for both the steel shot and silica sand respectively by the method of least squares. The resulting quadratic equation in the case of the steel shot is as follows:

$$d_{50\text{steel}} = 5.29 - 0.47 X_1 + 0.03 X_2 + 0.1 X_3 - 0.3 X_1 X_2 - 0.1 X_2 X_3 \\ + 0.1 X_1 X_3 + 0.26 X_1^2 + 0.36 x_2^2 + 0.05 x_3^2 \quad (2)$$

The corresponding analysis of variance is given in Table 12. The ratio of the lack of fit mean square and error mean square indicates that the quadratic equation represent the surface approximately. The residual sum of squares from the two center points was used as a measure of the error sum of squares. The coefficients of the linear order effects in equation (2) are small in magnitude compared with some of the two factor interactions, which suggest that the experimental points are in the near-stationary region. This line of evaluation will not be pursued further because a comparable analysis is not possible with the silica sand data.

It is apparent in Table 12 that the rotor speed is the most significant parameter. The main effect due to solids concentration appears to be rather small. However, there is a strong interaction between the rotor speed and pulp density and the quadratic effect is also significant. It may be necessary to drop off the pulp density-feed size and rotor speed-feed size interaction terms as well as the quadratic term relating to the feed size as their effects are smaller than their standard errors.

Within the experimental region covered, it appears that once adequate speed is chosen, most combinations of the feed size and pulp density would yield a comparable median size. Refer to Table 11.

A similar line of analysis applied to the silica sand data (also in Table 11) yields the following regression equation:

$$d_{50\text{ sand}} = 5.2 - 16.46 X_1 + 8.41 X_2 + 27.05 X_3 - 6.73 X_1 X_2 \\ + 11.64 X_2 X_3 - 9.39 X_1 X_3 + 9.6 x_1^2 - 0.25 x_2^2 + 18.09 x_3^2 \quad (3)$$

Table 11 Design Matrix and Results Obtained

Trial				Median Size (d ₅₀), (μm)	
	X1	X2	X3	Silica Sand	Steel Shots
1	-1	-1	-1	9.3	5.7
2	1	-1	-1	6.0	5.5
3	-1	1	-1	17.4	6.9
4	1	1	-1	10.6	5.3
5	-1	-1	1	25.27	5.9
6	1	-1	1	7.8	5.8
7	-1	1	1	103.32	6.38
8	1	1	1	35.55	5.49
9	0	0	0	10.4	5.2
10	0	0	0	11.4	5.54
11	-2	0	0	91.2	7.58
12	2	0	0	7.2	5.2
13	0	0	-2	7.2	5.22
14	0	0	2	159.29	5.9
15	0	-2	0	5.91	7.0
16	0	2	0	13.9	6.63

Table 12 Analysis of Variance of the Steel Shot Regression Equation

Source	Sum of Squares	Degree of Freedom	Mean Square	Ratio of Mean Squares
Constant b_0	566.92	1		
Main Effects:				
Speed b_1	3.54	1	3.54	$3.54 / 0.13 = 27.23$
Pulp Density b_2	0.01	1	0.01	
Feed Size b_3	0.15	1	0.15	$0.15 / 0.13 = 1.15$
Quadratic Order Effects:				
Speed b_{11}	0.34	1		
Pulp Density b_{22}	2.43	1		
Feed Size b_{33}	0.43	1		
				$1.03 / 0.13 = 7.92$
Total Square Terms:	3.10	3	1.03	
Interaction Effects:				
Speed–pulp Density b_{12}	0.60	1	0.6	$0.6 / 0.13 = 4.61$
Pulp–density – feed size b_{23}	0.009	1		
Speed–feed size b_{13}	0.08	1		
Lack of Fit	0.70	5	0.14	$0.14 / 0.13 = 2$
Error	0.07	1	0.07	
Residual	0.77	6	0.13	
Total	575.26	16		

The first order effects compared with some of the two factor interactions are fairly large and as such, some changes in the test design will be necessary in order to move the factor levels to the near-stationary region. It is not possible to make the required tests and incorporate the results here due to time limitations. But, the information derived from the present data is however, sufficient to highlight some of the differences which arise as a result of using the two grinding media types. Instead of questioning the adequacy of the quadratic model as suggested by the variance ratio (11.11), it would suffice to say that once the changes indicated above are made, the validity of the model will be assessed. The significant main effects are feed size and rotor speed as evident in Table 13. This is in contrast to the observation in the case of the steel grinding media. The implication is that the feed size and the rotor speed must be chosen with caution. When the feed consists of too large particles or the rotor speed is very low, the grinding performance of silica sand is greatly reduced. Similarly, high pulp densities tend to impair the performance. These situations are clearly shown in Table 11.

The product size distributions obtained from some of the test runs are plotted in Figures 10 and 11. The steel shots products in general, exhibit a higher degree of fineness compared to those with silica sand depending on the grinding condition. This result is expected, and a similar observation has been reported previously by researchers such as Mankosa, et al., 1986, and Davis. This feature can be attributed to the difference in either the media density or the media to coal ratio since the corresponding values of both are higher for the steel shot. The implication of result is that the unit capacity of the mill will be higher where steel shots are used as the grinding media. The energy consumption may however, be lower when silica sand is used as the grinding media. Preliminary data obtained here indicates that the ratio of the energy input of steel shot and silica sand systems varies between 1.3 to 2.5 depending on the test condition. Hence, it is possible to find an experimental region where silica sand can be used to produce coal particles of an identical fineness but, with a low specific energy. This observation is in contrast with that reported by Davis and tend to support the view expressed by Mehta and Schultz, 1991. The shape of the product size distributions obtained with the two media types are identical. Therefore, the breakage mechanisms of the two systems are similar, but, the breakage rate (min^{-1}) with steel shot is relatively higher compared with that of silica sand.

The calorific value, the fixed carbon and volatile matter contents of the coal ground with steel shots are relatively lower than in products with silica sand. Some of the products' characteristics are given in Table 14. This pattern is maintained even when analysis is made on dry basis. The trend display by the ash content is, however, altered on dry basis. Analysis of the coal ash indicates that the iron content of the steel shot products is twice the amount in corresponding

Fig. 9 Sample Holder for Making Cylindrical Cores

Figure 10 Product size distributions with grinding media type as parameter. Test conditions are: 2400 rpm, 8 minutes residence time, pulp density 20% weight and feed size 150 x 200 mesh.

Table 13 Analysis of Variance of the Silica Sand Regression Equation

Source	Sum of Squares	Degree of Freedom	Mean Square	Ratio of Mean Squares
Constant	17013.29	1		
Main Effects:				
Speed	4334.25	1	4334.25	$\frac{4334.25}{617.93} = 7.01$
Pulp Density	1130.30	1	1130.3	$1130.3/617.93 = 1.83$
Feed Size	11708.32	1	11708.32	$\frac{11708.32}{617.93} = 18.95$
Quadratic Order Effects:				
Speed b_{11}	316.10	1		
Pulp Density b_{22}	1841.90	1		
Feed Size b_{33}	5233.80	1		
				$\frac{2463.93}{617.93} = 3.99$
Total Square Terms:	7391.8	3	2463.93	
Interaction Effects:				
Speed–pulp Density	316.81	1		$\frac{1083.45}{617.93} = 1.75$
Pulp–density – feed size	1083.45	1	1083.45	
Speed–feed size	705.75	1		
Lack of Fit	3641.99	5	728.40	$728.4/65.57 = 11.11$
Error	65.57	1	65.57	
Residual	3707.56	6	617.93	
Total	47391.53	16		

Table 14 Coal Characterization

Proximate Analysis (wt. %)	Feed		Silica Sand		Steel Shot	
	(100 x 150 mesh)	(150 x 200 mesh)	Trial 12	Trial 2	Trial 12	Trial 2
	Trial 12	Trial 2				
Moisture	2.39	2.48	20.81	10.08	37.25	46.53
Volatile Matter	31.60	30.44	25.51	28.01	20.14	16.42
Fixed Carbon	61.24	61.48	49.43	55.91	38.72	33.00
Ash	4.77	5.60	4.25	6.00	3.89	4.05
(dry basis)			(5.37)	(6.67)	(6.20)	(7.58)
Calorific Value (BTU/lb)	14,088	14,024	11,345	11,423	9,145	7,344
Forms of Sulfur (wt,%)						
Pyritic	0.07	0.10	.06	—	0.071	—
Organic	0.56	0.51	0.464	—	0.316	—
Sulphate	0.08	0.10	0.046	—	0.053	—
Total Sulfur:	0.71	0.71	0.57	—	0.44	—
Coal Ash Analysis (wt,%)						
Chromium	0.001	0.001	0.001	0.001	0.003	0.004
Iron	0.220	0.345	0.270	0.226	0.538	0.525
Maganese	0.001	0.001	0.001	0.001	0.001	0.001
Nickel	0.002	0.003	0.005	0.005	0.002	0.002
Media Wear (kg/ton)	—	—	0.71		1.12	
(Average)

Figure 11 Product size distribution with grinding media type as parameter. Test conditions are : 2900 rpm, 8 minutes residence time, pulp density 30% weight and feed size 100 x 150 mesh.

silica sand products. The chromium content of the steel shot product also increases while that of silica sand is unchanged. The nickel content of the silica sand products are higher than those of steel shot products which is difficult to explain presently but future studies will be able to pinpoint as to what is causing such behavior. These increases in the heavy metal contents of the ash are the result of media wear which is estimated to have an average value of 1.12 kg/ton for steel shot and 0.71 kg/ton for silica sand. Another important observation worth noting in this table is the calorific value of the coal products. Note that the ground coal products' heating value remains practically the same when sand is used as grinding media but it decreases significantly and the extent of which depends upon the test condition.

Kinetic Analysis

Typical first order plots for both silica sand and steel shot products are shown in Figures 12 to 14. The curves exhibit non-linear characteristics. The degree of non-linearity is more pronounced with the silica sand products compared to those of steel shot. The non-linear characteristics imply that an initially high breakage rate slows down. Since the materials were dried prior to sieving, it is possible that the initial size distributions have been modified and as such, this must have contributed to the degree of non-linearity obtained. It should be born in mind that when the kinetic data are evaluated using specific energy inputs as a reduced time variable, a linear breakage behavior may be observe, and especially, the silica sand would turn out to have a higher grinding rate than steel shot.

On the basis of these results of Black Creek coal, we again establish that silica sand is a viable alternative grinding media for steel shot. However, the feed particle size and rotor speed or the grinding condition must be chosen prudently. the unit capacity of the mill will be slightly reduced when silica sand is used as a substitute for steel media.

The coal quality measured in terms of either the calorific value, fixed carbon content or volatile matter content is relatively higher when silica sand is used as grinding media compared to steel shot. The ash content of silica sand products on dry basis is relatively lower than that of steel shot. The contamination of the product by heavy metals such as chromium and iron in particular is greatly reduced when silica sand is used as grinding media. The nickel content of the silica sand product however, increases slightly which is unexplainable. The introduction of contaminants in products in general, should be reduced appreciably when silica sand is used as grinding media since the wear rate is low compared with steel shot.

Figure 12 First Order Disappearance Plot for 60 x 100 Mesh Black Creek Coal with 1400 rpm Stirring Speed and 20% wt. Pulp Density.

Figure 13 First Order Disappearance Plot for 60 x 100 Mesh Black Creek Coal with 2400 rpm Stirring Speed and 40% wt. Pulp Density.

Figure 14 First Order Disappearance Plot for 50 x 60 Mesh Black Creek Coal with 1900 rpm Stirring Speed and 30% wt. Pulp Density.

Table 15 Product Particle Size Distributions of Both Silica Sand and Steel Shot Grinding of Pocahontas #3

	Cumulative Weight Percent Passing								
Particle Size (µm)	Feed Size (mesh): Stirring Speed (rpm): Pulp Density (wt %):	150 x 200 2700 20		150 x 200 2700 40		60 x 100 1900 40		50 x 60 2300 30	
	Grinding Media:	Sand	Steel	Sand	Steel	Sand	Steel	Sand	Steel
24		100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
16		100.0	99.0	100.0	99.8	99.7	100.0	100.0	100.0
12		100.0	98.0	100.0	99.6	99.2	100.0	100.0	100.0
8		97.0	87.6	94.5	91.1	92.1	93.4	94.7	93.8
6		93.0	80.9	90.4	89.8	81.6	93.3	86.0	90.0
4		77.6	63.5	72.8	69.7	58.9	75.9	65.2	74.0
3		63.1	52.7	59.9	59.0	43.6	65.6	49.4	62.4
2		41.9	34.3	40.3	37.7	28.3	43.5	32.2	41.2
1.5		28.8	22.1	29.1	27.1	19.4	32.4	22.2	28.1
1		22.1	16.2	22.3	19.9	15.3	24.2	17.5	21.0
Specific Energy (kwh/ton):		884.65	1334.95	909.52	878.02	193.05	566.99	338.07	638.50

Table 16 Coal Characterization for Pocahontas #3 Coal

	Feed			Silica Sand				Steel Shot			
	50 x 60 mesh 14	60 x 100 mesh 7	150 x 200 mesh 2 ~ 4	Exp. 2	Exp. 4	Exp. 7	Exp. 14	Exp. 2	Exp. 4	Exp. 7	Exp. 14
Proximate Analysis (wt%)											
Moisture	1.05	1.09	1.10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Volatile Matter	17.65	17.58	17.64	18.55	18.19	18.34	18.50	18.65	18.09	18.42	18.29
Fixed Carbon	74.21	74.64	75.28	75.23	75.67	74.97	75.02	72.88	75.27	74.41	74.10
Ash	7.09	6.69	5.98	6.22	6.14	6.69	6.48	8.47	6.64	7.17	7.61
Calorific Value (BTU/lb)	14,655	16,715	14,863	14,289	14,244	13,455	14,127	14,290	14,326	14,241	13,940
Forms of Sulfur (Wt%)											
Pyritic	0.32	0.32	0.30	0.25	0.27	0.20	0.18	0.21	0.29	0.30	0.23
Organic	0.50	0.49	0.50	0.45	0.35	0.50	0.50	0.43	0.48	0.34	0.43
Sulphate	0.10	0.12	0.17	0.22	0.21	0.22	0.23	0.24	0.18	0.22	0.22
Total Sulfur	0.92	0.93	0.97	0.92	0.83	0.92	0.91	0.88	0.95	0.86	0.88
Coal Ash Analysis (wt%)											
Chromium	0.001	0.001	0.001	0.002	0.002	0.001	0.001	0.021	0.009	0.006	0.013
Iron	0.64	0.55	0.61	0.60	0.58	0.70	0.65	2.91	1.40	1.10	1.65
Nickel	0.003	0.003	0.00	0.003	0.004	0.002	0.002	0.002	0.003	0.002	0.030
Media Wear (kg/ton) (Average)				1.02				1.98			

Table 17 Design Matrix and Results for Pocahontas #3 Coal

Coded Variables				Silica Sand			Steel Shot		
Test No.	X ₁	X ₂	X ₃	d ₅₀ μm	d ₉₀ μm	Net energy kwh/ton	d ₅₀ μm	d ₉₀ μm	Net energy kwh/ton
1	-1	-1	-1	2.91	6.44	326.95	2.9	8.61	433.43
2	1	-1	-1	2.38	5.61	884.65	2.8	8.92	1334.95
3	-1	1	-1	3.36	7.68	232.90	2.5	5.89	402.86
4	1	1	-1	2.49	5.95	909.52	2.6	6.31	878.02
5	-1	-1	1	2.76	6.10	419.38	2.8	8.60	489.29
6	1	-1	1	2.28	5.37	861.50	2.8	9.10	1351.34
7	-1	1	1	3.42	7.60	193.05	2.3	5.62	566.99
8	1	1	1	2.80	6.84	855.65	2.6	6.42	1175.04
9	-2	0	0	4.43	10.15	238.19	2.7	6.38	299.94
10	2	0	0	2.75	6.30	1095.94	2.5	7.66	1801.12
11	0	0	-2	3.27	7.70	348.68	2.4	6.10	497.68
12	0	0	2	3.04	6.92	338.07	2.4	6.00	638.05
13	0	-2	0	2.17	5.37	1052.64	3.7	9.87	1600.54
14	0	2	0	3.47	9.61	334.43	3.1	9.28	442.60
15	0	0	0	2.92	6.93	321.77	2.5	6.44	548.31
16	0	0	0	2.76	6.21	319.59	2.5	6.28	529.91
17	0	0	0	2.90	6.52	408.51	2.3	5.71	602.86
18	0	0	0	2.80	6.33	352.59	2.5	6.83	627.41

The low costs of silica sand, the relatively low media charges required, the low wear rates and the associated low media replenishment cost should sum up to reduce the operating cost for coal-silica sand system compared to coal-steel media system.

E. Modified Batch Grinding Runs

Pocahontas #3 coal

This coal had a rather peculiar property in that it is soft as depicted by the corresponding high hardgrove indices and has clay constituents which exhibit swelling characteristics. The soft nature of the coal is reflected on the product fineness while the associated rapid changes in the slurry rheology result in a high specific energy consumption. This is particularly evident where silica sand is used as the grinding media. In addition, the rheological changes pose operating problems.

Some of the product size distributions obtained using both silica sand and steel shot respectively as grinding media are shown in Table 15. The products from the two systems have a similar degree of fineness. However, the steel shot system tends to consume more energy compared with the silica sand system.

A few of the products were subjected to some form of characterization such as proximate and ash (chemical) analyses, forms of sulfur, etc. in an effort to evaluate the impact of sand and steel media on the ground coal quality. The results of these are presented in Table 16. The magnitude of the difference in the calorific value, volatile matter, fixed carbon and nickel contents of the products of the two systems is rather small. However, the ash, iron and chromium contents of the steel shot products are higher than those of the corresponding silica sand products. Although the silica content in the sand products is expected to be higher than those of steel products, the substitution of steel media by silica sand would not necessarily impair the product (coal) quality.

The median and d_{90} sizes of the products and the specific energy consumption for the whole set of experiments on Pocahontas #3 coal are presented on Table 17. Analysis of the median size and specific energy consumption in terms of the experimental variables using the method of least squares shows that a second degree polynomial of the form given by equation (1) can be used to represent the data.

Table 18 Analysis of Variance for the Silica Sand
System Median Size Model Equation

<u>Source</u>	<u>Sum of Squares</u>	<u>D.F.</u>	<u>Mean Square</u>	<u>Mean Square Ratio</u>
Constant	156.06	1		
Main Effect				
Speed	2.18	1	2.18	34.88
Pulp Density	1.16	1	1.16	18.35
Feed Size	0.02	1	0.02	0.32
Quadratic Order Effect				
Speed	0.56	1		
Pulp Density	0.03	1		
Feed Size	<u>0.07</u>	<u>1</u>		
Total Sq. Terms	0.66	3	0.22	3.48
Interaction Effect				
Speed-Pulp Density	0.03	1	0.03	0.47
Speed-Feed Size	0.01	1	0.01	0.16
Pulp Density-Feed Size	0.03	1	0.03	0.49
Lack of Fit	0.47	5	0.094	8.46
Error	<u>0.03</u>	<u>3</u>	0.011	
Residual	0.51	8	0.06	
Total	160.66	18		

5,3,0.05 = 9.01

Table 19 Analysis of Variance for the Silica Sand
System Energy Model Equation

<u>Source</u>	<u>Sum of Squares</u>	<u>D.F.</u>	<u>Mean Square</u>	<u>Mean Square Ratio</u>
Constant	5007568	1		
Main Effect				
Speed	1027456	1	1027456	61.68
Pulp Density	188742.5	1	188742.5	11.33
Feed Size	130.30	1	130.30	0.008
Quadratic Order Effect				
Speed	96965.7	1		
Pulp Density	194758.5	1		
Feed Size	<u>193.3</u>	<u>1</u>		
Total Sq. Terms	291917.5	3	97305.83	5.84
Interaction Effect				
Speed-Pulp Density	14399.0	1	14399.0	0.86
Speed-Feed Size	2099.5	1	2099.5	0.13
Pulp Density-Feed Size	3321.1	1	3321.1	0.2
Lack of Fit	126643.4	5	25328.68	11.48
Error	<u>6616.8</u>	<u>3</u>	2205.6	
Residual	133260.2	8	16657.53	
Total	6668894.1	18		

Table 20 Analysis of Variance for the Steel Shot
System Median Size Model Equation

<u>Source</u>	<u>Sum of Squares</u>	<u>D.F.</u>	<u>Mean Square</u>	<u>Mean Square Ratio</u>
Constant	127.47	1		
Main Effect				
Speed	0.001	1	0.001	0.1
Pulp Density	0.391	1	0.391	39.1
Feed Size	0.006	1	0.006	0.6
Quadratic Order Effect				
Speed	0.009	1		
Pulp Density	1.389	1		
Feed Size	<u>0.006</u>	<u>1</u>		
Total Sq. Terms	1.404	3	0.468	46.8
Interaction Effect				
Speed-Pulp Density	0.031	1	0.031	3.1
Speed-Feed Size	0.011	1	0.011	1.1
Pulp Density-Feed Size	0.001	1	0.001	0.1
Lack of Fit	0.048	5	0.0096	0.96
Error	<u>0.031</u>	<u>3</u>	0.01	
Residual	0.079	8	0.01	
Total	129.39	18		

Table 21 Analysis of Variance for the Steel Shot
System Energy Size Model Equation

<u>Source</u>	<u>Sum of Squares</u>	<u>D.F.</u>	<u>Mean Square</u>	<u>Mean Square Ratio</u>
Constant	11234340.0	1		
Main Effect				
Speed	2138278	1	1027456	40.08
Pulp Density	526343	1	188742.5	7.36
Feed Size	41426.5	1	130.3	0.005
Quadratic Order Effect				
Speed	222677.6	1		
Pulp Density	309823.9	1		
Feed Size	<u>9.69</u>	<u>1</u>		
Total Sq. Terms	532511.2	3	177503.7	6.92
Interaction Effect				
Speed-Pulp Density	57861.2	1	57861.2	2.26
Speed-Feed Size	1090.9	1	1090.9	0.04
Pulp Density-Feed Size	18905.4	1	18905.4	0.74
Lack of Fit	198657.88	5	39731.58	18.55
Error	<u>642422</u>	<u>3</u>	214141	
Residual	205082.1	8	25635.26	
Total	14755838.3	18		

$$y = b_0 + \sum_{i=1}^3 b_i x_i + \sum_{i=1}^3 b_{ii} x_i^2 + \sum_{i=1}^3 \sum_{j=1}^3 b_{ij} x_i x_j \quad (1)$$

The resulting equations for the silica sand system are as follows:

$$d_{50} = 2.8 - 0.36 x_1 + 0.27 x_2 - 0.03 x_3 + 0.16 x_1^2 - 0.02 x_2^2 + 0.06 x_3^2 - 0.06 x_1 x_2 + 0.04 x_1 x_3 + 0.06 x_2 x_3 \quad (2)$$

$$E = 369.76 + 253.41 x_1 - 108.61 x_2 - 2.85 x_3 + 83.9 x_1^2 + 90.52 x_2^2 + 2.98 x_3^2 + 42.43 x_1 x_2 - 16.2 x_1 x_3 - 20.38 x_2 x_3 \quad (3)$$

While the steel shot system can be represented using the following:

$$d_{50} = 2.44 - 0.01 x_1 - 0.16 x_2 - 0.02 x_3 + 0.03 x_1^2 + 0.23 x_2^2 - 0.02 x_3^2 + 0.06 x_1 x_2 + 0.04 x_1 x_3 - 0.01 x_2 x_3 \quad (4)$$

$$E = 583.71 + 365.57 x_1 - 181.37 x_2 + 50.88 x_3 + 120 x_1^2 + 112.76 x_2^2 - 0.67 x_3^2 - 85.05 x_1 x_2 + 11.68 x_2 x_3 + 48.61 x_2 x_3 \quad (5)$$

The above equations explain over 80 % of the variations in the data. The corresponding analysis of variance for the model equations are given in Tables 18 – 21. It can be seen in Tables 18 and 19 that the agitation speed and pulp density are the only significant parameters. Both the quadratic and interaction effects are not significant. It is obvious in Table 17 that increasing agitation speed results in a gradual decrease in the product particle size distribution but the corresponding specific energy also increases. The pulp density on the other hand, has the opposite effect as increase in solids concentration leads to a simultaneous increase in product size while the specific energy decreases. The feed size tends to have a negligible effect within the range studied.

In the case of the steel shot system, the significant parameters in the product size are both the main and quadratic effects of the solids concentration. The agitation speed appears to be the only significant main effect in the power model. It is evident in Table 17 that increasing agitation speed in the steel shot system do not necessarily lead to improved performance as there is no

appreciable change in the product size distribution and the energy consumption tends to be high. The steel shot system tends to favor the use of high solids concentration since the use of low pulp densities results in both a large product particle size and a high energy consumption.

Although the lack of fit for some of the models seem to be rather high thereby raising doubts about their adequacy, this can be attributed to blocking effects. The data employed in evaluating the experimental error was made in two groups and the batch of tests were made after the belt and pulley were altered to yield finer product size distributions as well as high energy consumption.

Black Creek coal (Modified Tests)

Although the batch grinding tests were made with this coal during the preliminary runs, the results obtained necessitated the modification of the experimental conditions in subsequent works. Therefore, it was decided that the set of experiments should be repeated in order to ensure a common basis for the evaluation of the grinding/breakage characteristics of all the coals employed in this research work.

Table 22 shows some of the product size distributions obtained. The steel shot system evidently produces a slightly finer product size distribution compared with silica sand. However, the specific consumption of the steel shot system is about twice the amount consumed by the corresponding silica sand. The implication of this as indicated previously is that a longer residence time would be required for grinding especially hard coals with silica sand. Consequently, the unit capacity of silica sand system is expected to be slightly lower compared with that of steel shot. However, the silica sand system may have an energy advantage.

Table 23 shows the characterization of some of the ground materials and the corresponding feeds. There is only a slight difference in the volatile matter, fixed carbon and calorific values of the products of both the silica sand and steel shot systems. However, there are large differences in the ash, iron and chromium contents of the products from the two systems. These can be attributed to the wear of the steel media. Similarly, the silica contents of the products from the silica sand system will be higher than those from steel shot.

Table 24 shows the specific energy, median size and specific energy, median size and d_{90} for all the test runs with Black Creek coal. The median size and specific energy were correlated with the experimental variables using the method of least squares. The equations obtained for the

two systems are of the same form as indicated previously for Pocahontas coal and are as follows:

Silica Sand System:

$$d_{50} = 5.23 - 1.28 x_1 + 1.32 x_2 + 0.16 x_3 + 0.63 x_1^2 + 0.35 x_2^2 - 0.12 x_3^2 - 0.39 x_1 x_2 - 0.46 x_1 x_3 + 0.34 x_2 x_3 \quad (6)$$

$$E = 280.52 + 201.77 x_1 - 169.98 x_2 + 1.17 x_3 + 55.83 x_1^2 + 66.3 x_2^2 - 13.95 x_3^2 - 51.8 x_1 x_2 - 7.89 x_1 x_3 + 15.8 x_2 x_3 \quad (7)$$

Steel Shot System:

$$d_{50} = 4.34 - 0.13 x_1 - 0.23 x_2 + 0.08 x_3 + 0.04 x_1^2 + 0.24 x_2^2 - 0.002 x_3^2 + 0.03 x_1 x_3 + 0.08 x_2 x_3 \quad (8)$$

$$E = 645.97 + 422.86 x_1 - 356.89 x_2 + 2.15 x_3 + 123.75 x_1^2 + 102.73 x_2^2 - 38.23 x_3^2 - 106.52 x_1 x_2 - 43.63 x_1 x_3 - 2.87 x_2 x_3 \quad (9)$$

These model equations explain over 80 % of the variations in the data and as such can be considered to be fairly good. The analysis of variance for the respective model equations are given in Tables 25 through 28. It can be seen that for the silica sand system, speed and solids concentration are the significant parameters for both the product size and specific energy. As for the steel shot system, solids concentration appears to be the only significant parameter in the product size model while both speed and pulp density are the significant factors in the specific energy model. The implications of these can be deduced from Table 24, where it can be seen in the case of silica sand that the media size decreases with decreasing pulp density and increasing stirring speed on product size is marginal. For both systems, low pulp densities and high agitation speed lead to high energy consumption.

Pittsburgh #8 Coal

A Pittsburgh #8 coal sample obtained from Southern Company Services in Wilsonville, Alabama was used in this work. The sample was dried at a low temperature for two days. Then it was crushed in stages using a jaw crusher and simultaneously screened with a 50 mesh sieve. The resulting coarse fraction was further ground in a roller mill to a minus 50 mesh size. Thereafter, the monodispersed feed sizes required were prepared from the minus 50 mesh material. The grinding tests were carried out using a modified Denver flotation machine equipped with a grinding

Table 22 Product Particle Size Distributions of Both Silica Sand and Steel Shot Grinding of Black Creek Coal

	Cumulative Weight Percent Passing								
Particle Size (µm)	Feed Size (mesh): Stirring Speed (rpm): Pulp Density (wt %):	150 x 200 2700 20		150 x 200 2700 40		60 x 100 1900 40		50 x 60 2300 30	
	Grinding Media:	Sand	Steel	Sand	Steel	Sand	Steel	Sand	Steel
24		99.9	100.0	99.4	100.0	66.0	100.0	96.8	100.0
16		98.6	97.8	94.4	98.2	57.9	98.0	94.4	97.6
12		96.3	94.1	86.7	95.7	57.9	93.4	88.8	93.0
8		86.3	78.3	64.2	84.1	42.8	80.5	76.0	79.6
6		73.3	64.6	47.4	70.9	36.8	65.5	61.3	65.9
4		48.3	42.1	28.6	46.6	21.2	42.0	39.8	43.2
3		33.3	30.0	20.6	32.5	16.2	28.8	27.5	29.8
2		20.3	17.5	13.3	19.8	9.5	17.9	17.5	17.8
1.5		13.1	10.2	8.4	12.6	6.5	11.4	11.0	11.1
1		10.1	7.5	6.4	9.7	4.6	8.9	8.6	8.6
Specific Energy (kwh/ton)		744.87	1602.61	446.56	703.67	120.52	224.15	276.23	550.93

Table 23. Coal Characterization for Black Creek Coal

	Feed			Silica Sand				Steel Shot			
	50 x 60 mesh 14	60 x 100 mesh 7	150 x 200 mesh 2 & 4	Exp. 2	Exp. 4	Exp. 7	Exp. 14	Exp. 2	Exp. 4	Exp. 7	Exp. 14
Proximate Analysis (wt%)											
Moisture	2.21	2.38	2.48	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Volatile Matter	32.94	32.32	30.44	31.10	31.15	32.85	33.46	29.68	30.01	31.93	32.43
Fixed Carbon	60.08	60.88	61.48	62.63	62.64	62.58	62.27	61.11	62.73	62.53	61.25
Ash	4.77	4.42	5.60	6.27	6.21	4.57	4.27	9.21	7.26	5.54	6.32
Calorific Value (BTU/lb)	14,258	14,469	14,024	13,804	13,851	14,406	13,900	13,504	13,504	13,483	13,821
Forms of Sulfur (Wt%)	0.07	0.06	0.10	0.09	0.07	0.06	0.05	0.12	0.12	0.08	0.07
Pyritic	0.57	0.58	0.51	0.54	0.54	0.58	0.59	0.39	0.41	0.52	0.51
Organic	0.08	0.08	0.10	0.09	0.08	0.06	0.05	0.16	0.16	0.10	0.09
Sulphate	0.72	0.72	0.71	0.72	0.69	0.69	0.67	0.67	0.67	0.70	0.67
Total Sulfur											
Coal Ash Analysis (wt%)											
Chromium	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.028	0.012	0.008	0.011
Iron	0.183	0.192	0.345	0.31	0.27	0.19	0.35	2.83	1.64	0.98	1.44
Nickel	0.003	0.002	0.003	0.003	0.004	0.003	0.003	0.010	0.003	0.003	0.005
Media Wear (kg/ton) (Average)											

Table 24. Design Matrix and Results for Black Creek Coal

	Coded Variables			Silica Sand			Steel Shot		
Test No.	X ₁	X ₂	X ₃	d ₅₀ μm	d ₉₀ μm	Net energy kwh/ton	d ₅₀ μm	d ₉₀ μm	Net energy kwh/ton
1	-1	-1	-1	4.6	10.52	231.52	5.1	11.44	513.91
2	1	-1	-1	4.1	9.45	744.87	4.7	10.96	1602.61
3	-1	1	-1	6.8	15.42	39.60	4.5	10.18	172.11
4	1	1	-1	6.3	13.71	446.56	4.3	10.03	703.67
5	-1	-1	1	4.8	98.05	150.41	4.8	11.48	685.53
6	1	-1	1	4.0	9.61	733.03	4.7	10.78	1468.68
7	-1	1	1	9.9	124.43	120.52	4.7	10.95	224.15
8	1	1	1	6.0	46.22	395.12	4.4	10.35	712.26
9	-2	0	0	11.7	117.55	172.12	4.7	10.83	246.26
10	2	0	0	4.3	11.10	897.50	4.2	10.32	2183.36
11	0	0	-2	5.1	10.94	235.16	4.0	9.25	582.91
12	0	0	2	4.9	12.86	276.23	4.6	11.10	550.93
13	0	-2	0	4.5	11.53	1042.10	5.8	12.15	1943.70
14	0	2	0	9.3	79.00	111.29	4.7	11.10	317.83
15	0	0	0	5.5	15.24	227.17	4.5	10.72	531.46
16	0	0	0	5.7	15.89	385.67	4.2	10.23	667.32
17	0	0	0	5.3	13.63	254.14	4.4	10.66	791.20
18	0	0	0	4.9	12.51	317.09	4.2	10.21	741.63

Table 25 Analysis of Variance for the Silica Sand
System Median Size Model Equation

<u>Source</u>	<u>Sum of Squares</u>	<u>D.F.</u>	<u>Mean Square</u>	<u>Mean Square Ratio</u>
Constant	644.4	1		
Main Effect				
Speed	26.3	1	2.63	24.18
Pulp Density	27.8	1	27.8	25.56
Feed Size	0.4	1	0.4	0.37
Quadratic Order Effect				
Speed	8.46	1		
Pulp Density	3.74	1		
Feed Size	<u>0.32</u>	<u>1</u>		
Total Sq. Terms	12.52	3	4.17	3.84
Interaction Effect				
Speed-Pulp Density	1.2	1	1.2	1.10
Speed-Feed Size	1.7	1	1.7	1.56
Pulp Density-Feed Size	0.9	1	0.9	0.83
Lack of Fit	8.28	5	1.66	11.8
Error	<u>0.42</u>	<u>3</u>	0.14	
Residual	8.7	8	1.09	
Total	723.92	18		

$F_{3,0.05} = 9.01$

Table 26. Analysis of Variance for the Silica Sand
System Energy Size Model Equation

<u>Source</u>	<u>Sum of Squares</u>	<u>D.F.</u>	<u>Mean Square</u>	<u>Mean Square Ratio</u>
Constant	2553875	1		
Main Effect				
Speed	651366	1	651366	49.44
Pulp Density	462281	1	462281	35.08
Feed Size	21.79	1	21.79	0.002
Quadratic Order Effect				
Speed	48086.3	1		
Pulp Density	121465.9	1	121465.9	9.22
Feed Size	<u>4248.3</u>	<u>1</u>	57933.5	4.40
Total Sq. Terms	173800.5	3		
Interaction Effect				
Speed-Pulp Density	21466.96	1	21466.96	1.63
Speed-Feed Size	497.54	1	497.54	0.04
Pulp Density-Feed Size	1873.64	1	1873.64	0.14
Lack of Fit	89472.88	5	17894.58	
Error	<u>15935.52</u>	<u>3</u>	5311.84	3.37
Residual	150408.4	8	13176.05	
Total	3970590.83	18		

Table 27 Analysis of Variance for the Steel Shot
System Median Size Model Equation

<u>Source</u>	<u>Sum of Squares</u>	<u>D.F.</u>	<u>Mean Square</u>	<u>Mean Square Ratio</u>
Constant	378.13	1		
Main Effect				
Speed	0.25	1	0.25	8.42
Pulp Density	0.81	1	0.81	27.27
Feed Size	0.09	1	0.09	3.03
Quadratic Order Effect				
Speed	0.011	1	1.356	45.64
Pulp Density	1.356	1		
Feed Size	<u>0.0001</u>	<u>1</u>		
Total Sq. Terms	1.3671	3	0.456	15.34
Interaction Effect				
Speed-Pulp Density	0.0	1	0.0	0.0
Speed-Feed Size	0.005	1	0.005	0.17
Pulp Density-Feed Size	0.045	1	0.045	1.51
Lack of Fit	0.169	5	0.034	1.47
Error	<u>0.069</u>	<u>3</u>	0.023	
Residual	0.238	8	0.03	
Total	380.93	18		

Table 28 Analysis of Variance for the Steel Shot
System Energy Size Model Equation

<u>Source</u>	<u>Sum of Squares</u>	<u>D.F.</u>	<u>Mean Square</u>	<u>Mean Square Ratio</u>
Constant	11906420	1		
Main Effect				
Speed	2860936	1	2860936	99.47
Pulp Density	2037956	1	2037956	70.86
Feed Size	73.79	1	73.79	0.003
Quadratic Order Effect				
Speed	301643.3	1	301643.3	10.49
Pulp Density	320472.1	1	320472.1	11.14
Feed Size	<u>31884.5</u>	<u>1</u>		
Total Sq. Terms	653999.9	3	217999.97	7.58
Interaction Effect				
Speed-Pulp Density	90776.3	1	90776.3	3.16
Speed-Feed Size	15225.1	1	15225.1	0.53
Pulp Density-Feed Size	65.78	1	65.78	0.002
Lack of Fit	186280.33	5	37256.07	2.55
Error	<u>43809.97</u>	<u>3</u>	14603.32	
Residual	230090.3	8	28761.29	
Total	17795543.2	18		

chamber and rotor configuration shown in Figure 7.

The chamber has a net volume of 230 ml and about 60 % of the volume was filled with both grinding media and slurry during each test in order to minimize spillage. Silica sand and steel shots of about 1mm size were used as grinding media. The volumetric filling was kept constant for the two media types. Batch grinding method was employed. Once the rotor was set in place, the required amount of grinding media was introduced followed by coal and water prior to the commencement of grinding. The time duration used for each test was fixed at 12 minutes. The grinding media were separated by screening at the end of each test. The particle size distribution of the products were analysed using Cilas granulometre 715.

Composite factorial design (Box, 1954), was used to study the effect of rotor speed, solid concentration and feed size on the grinding performance of the two media types. The levels of the factors used in the experiments are given in Table 29. The standardized variables X1, X2 and X3 are expressed in terms of the natural variables as follows:

$$X_1 = \frac{s-2300}{400}, \quad X_2 = \frac{c-30}{10}, \quad X_3 = \frac{150-f}{50} \quad (1)$$

Note that the standardized form for X3 is only an approximation. The design consists of eighteen points including replicates in coded variables. The coded factors and measured responses are given in Table 30.

Model Equation

A second degree polynomial of the form as depicted by the following equation (2) was assumed to represent the responses (median size and net energy consumption) based on the experimental design employed and therefore, was fitted to the data.

$$Y = b_0 + b_1X_1 + b_2X_2 + b_3X_3 + b_{11}X_1^2 + b_{22}X_2^2 + b_{33}X_3^2 + b_{12}X_1X_2 + b_{13}X_1X_3 + b_{23}X_2X_3 \quad (2)$$

The resulting equations for the median size and specific energy respectively for the silica sand system are as follows:

Table 29 Experimental Factors and Levels

Factors	Levels				
	-2	-1	0	1	2
s: Rotor Speed (rpm)	1500	1900	2300	2700	3100
c: Coal Concentration (wt,%)	10	20	30	40	50
f: Feed Size (mesh)	200 x 270	150 x 200	100 x 150	60 x 100	50 x 60

Table 30 Design Matrix and Results

Test				Silica Sand		Steel Shot	
	X1	X2	X3	d50 μm	Net Energy Kwh/ton	d50 μm	Net Energy Kwh/ton
1	-1	-1	-1	3.74	122.58	4.01	623.57
2	1	-1	-1	3.44	809.61	3.79	1455.26
3	-1	1	-1	5.01	72.45	3.38	267.84
4	1	1	-1	4.04	477.97	3.32	690.87
5	-1	-1	1	3.75	314.75	4.16	431.19
6	1	-1	1	3.76	713.16	4.12	1500.54
7	-1	1	1	4.73	48.36	3.52	238.94
8	1	1	1	4.01	436.98	3.86	717.46
9	-2	0	0	5.07	164.35	3.48	333.51
10	2	0	0	3.75	1056.02	3.62	2115.05
11	0	0	-2	3.91	213.21	3.34	636.81
12	0	0	2	4.09	409.41	3.84	531.83
13	0	-2	0	3.66	699.38	5.25	1594.30
14	0	2	0	4.96	127.26	3.46	393.30
15	0	0	0	3.96	307.87	3.51	567.88
16	0	0	0	3.73	228.55	3.47	611.05
17	0	0	0	3.4	330.27	3.40	851.27
18	0	0	0	3.4	361.16	3.50	754.10

$$d_{50} = 3.61 - 0.29 X_1 + 0.35 X_2 + 0.04 X_3 + 0.20 X_1^2 + 0.18 X_2^2 + 0.09 X_3^2 - 0.18 X_1 X_2 + 0.08 X_1 X_3 - 0.1 X_2 X_3 \quad (3)$$

$$E = 297.37 + 228.93 X_1 - 129.29 X_2 + 26.44 X_3 + 73.41 X_1^2 + 24.19 X_2^2 - 1.31 X_3^2 - 36.41 X_1 X_2 - 38.19 X_1 X_3 - 20.1 X_2 X_3 \quad (4)$$

The corresponding equations for the steel shot system are as follows:

$$d_{50} = 3.48 + 0.01 X_1 - 0.35 X_2 + 0.14 X_3 + 0.20 X_1^2 + 0.23 X_2^2 + 0.02 X_3^2 + 0.08 X_1 X_2 + 0.08 X_1 X_3 + 0.03 X_2 X_3 \quad (5)$$

$$E = 660.37 + 397.85 X_1 - 281.09 X_2 - 22.46 X_3 + 123.12 X_1^2 + 65.50 X_2^2 - 36.87 X_3^2 - 124.94 X_1 X_2 + 36.64 X_1 X_3 + 18.10 X_2 X_3 \quad (6)$$

The above equations explain over 85 % of the variations in the data. The analysis of variance for the four model equations are presented in Tables 31–34. It can be deduced from the insignificance of the lack of fit that the respective models represent the data adequately. It appears that the agitation speed and pulp density are the only parameters which have significant effects. The feed size and interaction effects are in general insignificant. This does not necessarily imply that they are unimportant.

Analysis of Fitted Model Equations

In order to determine the optimal conditions, the system of conics corresponding to the response surfaces were reduced to the canonical form. This consists primarily of shifting the origin of the contour surfaces to the stationary point and subsequently rotating the axes to correspond with those of the conics. Thus, the contour surfaces in terms of a set of orthogonal co-ordinates are given by the following equation (7).

$$y - y^0 = l_1 X_1^2 + l_2 X_2^2 + l_3 X_3^2 \quad (7)$$

The predicted response at the stationary point (y^o) was calculated using the following equation:

$$y^o = b_o + 1/2 \sum_{i=1}^3 b_i x_i \quad (8)$$

Details of how to make the required calculations have been published by Box (1987), Box and Wilson (1951) and can be found in many statistics textbooks. The canonical forms of the response surfaces equations 3 & 4 for silica sand system are as follows:

$$d_{50} = 3.84 + 0.08 x_1^2 + 0.11 x_2^2 + 0.30 x_3^2 \quad (9)$$

The transformation of X in terms of the original co-ordinates is given by equation (10).

$$\begin{aligned} X_1 &= 0.02 X_1 + 0.43 X_2 + 0.90 X_3 + 0.80 \\ X_2 &= 0.70 X_1 + 0.64 X_2 - 0.32 X_3 + 0.15 \\ X_3 &= 0.71 X_1 - 0.64 X_2 + 0.28 X_3 - 0.74 \end{aligned} \quad (10)$$

$$E = 528.36 - 11.81 x_1^2 + 25.87 x_2^2 + 82.23 x_3^2 \quad (11)$$

Where

$$\begin{aligned} X_1 &= 0.28 X_1 + 0.39 X_2 + 0.88 X_3 - 158 \\ X_2 &= 0.16 X_1 + 0.88 X_2 - 0.44 X_3 - 1.72 \\ X_3 &= 0.95 X_1 - 0.26 X_2 - 0.18 X_3 + 1.50 \end{aligned} \quad (12)$$

The corresponding canonical forms of the response surfaces equations 5 & 6 for the steel shot system are as follows:

$$d_{50} = 3.70 - 0.02 x_1^2 + 0.05 x_2^2 + 0.24 x_3^2 \quad (13)$$

with the transformation for X as:

$$\begin{aligned} X_1 &= 0.73 X_1 - 0.07 X_2 - 0.68 X_3 + 1.68 \\ X_2 &= 0.66 X_1 - 0.19 X_2 + 0.73 X_3 + 1.69 \\ X_3 &= 0.18 X_1 + 0.98 X_2 + 0.09 X_3 - 0.68 \end{aligned} \quad (14)$$

$$E = 1020.65 - 41.95 X_1^2 + 30.04 X_2^2 + 163.67 X_3^2 \quad (15)$$

while the transformation is given as:

$$\begin{aligned} X_1 &= 0.18 X_1 - 0.18 X_2 - 0.97 X_3 + 0.48 \\ X_2 &= 0.51 X_1 - 0.83 X_2 + 0.25 X_3 - 0.61 \\ X_3 &= 0.85 X_1 - 0.53 X_2 + 0.05 X_3 + 1.48 \end{aligned} \quad (16)$$

When the predicted yield at the centers (stationary points) of the fitted functions (equations 9, 11, 13, and 15) are compared with the corresponding experimental results in Table 30, it is observed that they lie within the respective experiment regions. Hence, the fitted models represent the data and the co-ordinates of the stationary points should give estimates of the optimal operating conditions. The optimum conditions for the silica sand system are 2460 rpm, 21 % solids, 170 mesh for the median size and 2021 rpm, 41 % solids, 150 mesh for the median size and 1958 rpm, 44 % solids, 170 mesh for the specific energy. However, since no further confirmatory experiments were made, the above estimates for the optimal conditions should be considered as approximate values.

Since the coefficients of equation 9 are all positive, the fitted surface has a minimum at the stationary point. While in the cases of equations 11, 13 & 15, the form of the surfaces is a col or minimax since the coefficients of X_1 is negative. The surfaces are attenuated along the axes with the smallest coefficients which for equations 9, 11 & 13 are the X_1 axes respectively and the X_2 axis in the case of equation 15, since the X_3 term is the predominant factor in equations 9, 11, 13 & 15, it can be deduced that any movement from the stationary points in the direction of X_3 axis will lead to relative'y rapid movement in the yield while changes in X_2 will only have relatively smaller effect. Whereas, any further changes in the factors having negative coefficients would only lead to a deterioration in yield (product size or specific energy).

Table 31 Analysis of Variance for the Silica Sand System Median Size Model Equation

<u>Source</u>	<u>Sum of Squares</u>	<u>D.F.</u>	<u>Mean Square</u>	<u>Mean Square Ratio</u>
Constant	292.01	1		
Main Effect				
Speed	1.32	1	1.32	35.68
Pulp Density	1.96	1	1.96	52.97
Feed Size	0.02	1	0.02	0.54
Quadratic Order Effect				
Speed	0.49	1		13.24
Pulp Density	0.54	1		14.59
Feed Size	0.18	1		4.86
Total Sq. Terms	1.21	3	0.4	10.9
Interaction Effect				
Speed-Pulp Density	0.25	1	0.25	6.76
Speed-Feed Size	0.05	1	0.05	1.35
Pulp Density-Feed size	0.08	1	0.08	2.16
Lack of Fit	0.048	5	0.0095	0.11
Error	0.248	3	0.083	
Residual	0.296	8	0.037	
Total	297.2	18		

Table 32 Analysis of Variance for the Silica Sand System Specific Energy Model Equation

<u>Source</u>	<u>Sum of Squares</u>	<u>D.F.</u>	<u>Mean Square</u>	<u>Mean Square Ratio</u>
Constant	2639881	1		
Main Effect				
Speed	838561.4	1	838561.4	185.54
Pulp Density	267438.9	1	267438.9	59.17
Feed Size	11185.2	1	11185.2	2.47
Quadratic Order Effect				
Speed	118796.3	1		26.28
Pulp Density	14702.5	1		3.25
Feed Size	37.4	1		
Total Sq. Terms	133536.2	3	44512.07	9.85
Interaction Effect				
Speed–Pulp Density	10606.96	1	10606.96	2.35
Speed–Feed Size	11667.81	1	11667.81	2.58
Pulp Density–Feed size	3232.08	1	3232.08	0.72
Lack of Fit	26159.18	5	5231.84	1.57
Error	997.75	3	3332.58	
Residual	36156.93	8	4519.62	
Total	3952266.48	18		

Table 33 Analysis of Variance for the Steel Shot System Specific Energy Model Equation

<u>Source</u>	<u>Sum of Squares</u>	<u>D.F.</u>	<u>Mean Square</u>	<u>Mean Square Ratio</u>
Constant	250.13	1		
Main Effect				
Speed	0.003	1	0.003	0.12
Pulp Density	1.96	1	1.96	79.73
Feed Size	0.303	1	0.303	12.33
Quadratic Order Effect				
Speed	0.01	1		0.41
Pulp Density	1.19	1		48.31
Feed Size	<u>0.01</u>	<u>1</u>		0.41
Total Sq. Terms	1.21	3	0.4	16.38
Interaction Effect				
Speed-Pulp Density	0.045	1	0.045	1.83
Speed-Feed Size	0.045	1	0.045	1.83
Pulp Density-Feed size	0.005	1	0.005	0.20
Lack of Fit	0.189	5	0.038333	14.57
Error	<u>0.008</u>	<u>3</u>	0.0026	
Residual	0.197	8	0.025	
Total	253.9	18		

Table 34 Analysis of Variance for the Steel Shot System Specific Energy Model Equation

<u>Source</u>	<u>Sum of Squares</u>	<u>D.F.</u>	<u>Mean Square</u>	<u>Mean Square Ratio</u>
Constant	11384040	1		
Main Effect				
Speed	2532610	1	2532610	116.43
Pulp Density	1264191	1	1264191	58.12
Feed Size	8071.68	1	8071.68	0.37
Quadriatic Order Effect				
Speed	348130.8	1		16.0
Pulp Density	144807.8	1		6.66
Feed Size	<u>29653.27</u>	<u>1</u>		1.36
Total Sq. Terms	522591.87	3	174197.29	8.01
Interaction Effect				
Speed-Pulp Density	124872.5	1	124872.5	5.74
Speed-Feed Size	10742.12	1	10742.12	0.49
Pulp Density-Feed size	2620.52	1	2620.52	0.12
Lack of Fit	117805.96	5	23561.19	1.26
Error	<u>56216.24</u>	<u>3</u>	18738.75	
Residual	174022.2	8	21752.78	
Total	16023761.89	18		

Illinois #6 Coal

Illinois #6 coal was the last one used in the series of batch grinding tests. The test conditions were the same as those employed previously. Some of the resultant product size distributions are given in Table 35. It is obvious that both the silica sand and steel shot yield products having a fairly similar degree of fineness. The difference in the products tends to be pronounced at the tails of the size distribution. The most distinct feature between the two systems as depicted in Table 35 appears to be the specific energy. Evidently, the specific energy of the steel shot system is approximately twice that of the silica sand. This difference in energy consumption is attributable to the denser or heavier nature of the steel media compared to silica sand, since more energy is required to keep the former in motion. The relatively higher friction/shear arising from the movements or forcedly induced motions of the steel media also account for the apparent slight difference in the fineness of some of the products.

As in previous cases, a selected number of the products were subjected to such characterizations as proximate and ash (chemical) analyses, forms of sulfur determination, etc., in order to access the influence of silica and steel media, if any, on the ground coal quality. The results of these are shown in Table 36. The only discernable difference in the products of the two systems is in the ash contents and composition. The ash contents of the steel media products tend to be slightly higher, which can be attributed to the wear of the media. In addition, the chromium and iron (Fe) contents of the respective ash are also higher in the case of steel media products compared to those of silica sand products.

The products size as depicted by the median size and d90 as well as the specific energy for the whole set of experiments are given in Table 37. While the products from the steel shot system are relatively finer than those of the silica sand, the specific energy of the former is about twice those of the latter. Therefore, it can be inferred that the silica sand system will have a relatively lower unit output capacity compared with the steel shot system, but the silica sand system will be comparatively energy efficient.

The products median size and specific energy consumption were correlated with the experimental variables using the method of least squares. The resulting equations for the silica sand systems are as follows:

$$d_{50} = 5.79 - 0.44X_1 + 0.92X_2 - 0.03X_3 + 0.09X_1^2 - 0.003X_2^2 - 0.09X_3^2 - 0.29X_1X_2 + 0.19X_1X_3 - 0.06X_2X_3 \quad (1)$$

Table 35 Product Particle Size Distributions of Both Silica Sand and Steel Shot Grinding of Illinois #6

Particle Size (Micron)	Cumulative Weight Percent Passing								
	Feed Size (Mesh):	150 x 200		150 x 200		60 x 100		50 x 60	
	Stirring Speed (rpm):	2700		2700		1900		2300	
	Pulp Density (Wt. %):	20		40		40		30	
	Grinding Media:	Sand	Steel	Sand	Steel	Sand	Steel	Sand	Steel
24		99.20	100.00	100.00	100.00	89.60	100.00	94.90	100.00
16		98.30	98.70	98.80	98.90	83.50	99.00	90.10	98.70
12		95.80	95.20	91.30	97.00	76.00	96.60	85.50	95.60
8		82.50	80.20	71.20	85.70	57.70	83.00	67.80	81.80
6		68.20	65.80	53.50	72.80	45.00	68.30	54.30	67.30
4		44.40	43.00	34.20	49.60	29.50	45.10	34.70	44.40
3		31.80	30.80	25.30	36.60	22.10	33.10	25.80	31.90
2		19.20	18.10	16.80	23.40	14.00	24.10	16.40	19.60
1.5		11.00	9.90	9.70	14.00	8.00	12.70	9.60	11.10
1		8.00	7.00	7.10	10.30	5.80	9.30	6.90	8.10
Specific Energy (Kwh/ton)		972.61	2149.22	457.34	850.13	178.77	291.41	301.99	819.70

Table 36 Coal Characterization for Illinois #6 Coal

	Feed			Silica Sand				Steel Shot			
	50 x 60 mesh 12	60 x 100 mesh 7	150 x 200 mesh 2 x 4	Exp. 2	Exp. 4	Exp. 7	Exp. 12	Exp. 2	Exp. 4	Exp. 7	Exp. 12
Proximate Analysis (wt.%)											
Moisture	8.18	8.54	8.82	0	0	0	0	0	0	0	0
Volatile Matter	35.48	35.88	35.1	38.49	37.87	38.36	38.13	34.6	35.83	36.28	35.02
Fixed Carbon	45.36	46.12	46.78	53.07	52.51	51.57	51.46	51.18	53.51	52.89	53.22
Ash	10.98	9.46	9.3	8.44	9.62	10.07	10.41	14.02	10.66	10.83	11.76
Calorific Value (BTU/lb)	11,587	11,628	11,491	12,281	12,344	12,616	12,546	12,535	11,993	12,220	12,076
Form of Sulfur (wt%)											
Pyritic	0.94	0.81	0.82	1.11	1.01	0.91	1.13	1.2	1.15	1.12	1.4
Organic	1.69	1.73	1.71	1.25	1.17	1.29	1.19	0.78	1.05	1.12	0.77
Sulphate	0.58	0.48	0.44	0.37	0.44	0.57	0.41	0.57	0.45	0.54	0.47
Total Sulfur	3.21	3.02	2.97	2.73	2.62	2.77	2.73	2.55	2.65	2.78	2.64
Coal Ash Analysis (wt%)											
Chromium	0.002	0.002	0.002	0.004	0.002	0.002	0.003	0.052	0.016	0.013	0.024
Iron	1.35	1.325	1.252	1.22	1.15	1.17	1.13	4.8	2.35	2.3	2.73
Nickel	0.004	0.002	0.002	0.003	0.003	0.002	0.003	0.007	0.002	0.004	0.004

Table 37 Design Matrix and Results

Test Number	Coded Variables			Silica Sand			Steel Shot		
	X1	X2	X3	d50 mm	d90 mm	net energy KWH/ton	d50 mm	d90 mm	net energy KWH/ton
1	-1	-1	-1	4.9	10.79	214.03	5	11.07	644.51
2	1	-1	-1	4.5	10.26	972.61	4.6	10.61	2149.22
3	-1	1	-1	7.7	15.91	193.14	4.3	9.82	362.74
4	1	1	-1	5.6	11.74	457.34	4	9.52	850.13
5	-1	-1	1	4.8	11.36	188.31	4.7	10.73	995.86
6	1	-1	1	4.6	10.57	1067.16	5.1	11.37	1708.44
7	-1	1	1	6.8	36.57	178.77	4.4	10.06	291.44
8	1	1	1	6	13.33	541.27	4	9.66	996.57
9	-2	0	0	7.2	16.35	152.28	4.6	10.49	408.49
10	2	0	0	5.4	11.45	1036.35	4.4	10.5	2221.11
11	0	0	-2	5.6	11.65	370	4.4	10.28	586.01
12	0	0	2	5.6	15.91	301.99	4.5	10.39	819.7
13	0	-2	0	4.1	9.48	959	6.5	13.22	1878.39
14	0	2	0	7.8	18.04	230.09	4.5	10.56	477.99
15	0	0	0	6.1	12.81	259.41	4.4	10.05	648.89
16	0	0	0	5.7	12.1	390.68	4.5	10.39	554.69
17	0	0	0	5.9	11.55	362.4	4.3	9.5	600.6
18	0	0	0	5.8	11.2	356.62	4.2	10.07	582.6

$$E = 344.89 + 252.02X_1 - 158.09X_2 + 0.15X_3 + 63.66X_1^2 + 63.72X_2^2 - 0.92X_3^2 - 126.34X_1X_2 + 27.32X_1X_3 + 0.09X_2X_3 \quad (2)$$

where X_1 = rotor speed, X_2 = solids concentration and X_3 = feed size.

While the corresponding equations for the steel shot are:

$$d_{50} = 4.3 - 0.07X_1 - 0.42X_2 + 0.03X_3 + 0.03X_1^2 + 0.28X_2^2 + 0.01X_3^2 - 0.09X_1X_2 + 0.09X_1X_3 - 0.01X_2X_3 \quad (3)$$

$$E = 610.49 + 439.69X_1 - 362.7X_2 + 28.32X_3 + 182.98X_1^2 + 148.82X_2^2 + 29.99X_3^2 - 128.09X_1X_2 - 71.8X_1X_3 + 20.57X_2X_3 \quad (4)$$

The above equations account for between 80-95% of the variations in the data. The analysis of variance for the respective equations are given in Tables 38-41. It can be seen from the lack of fit that the model equations represent the data adequately. Depending on the model equation, it is evident that some of the parameters are significant at the 95% confidence level, while others are not. Rather than attach any particular importance to these, we would proceed with further evaluations to determine the optimum conditions for the respective systems.

Optimization of Process Parameters

The fitted model equations (1 - 4) given above were converted into the canonical forms in attempts to determine the optimal conditions. The resulting contour surfaces in terms of orthogonal coordinates are given by equation of the following form:

$$Y = Y_0 + |_1X_1^2 + |_2X_2^2 + |_3X_3^2 \quad (5)$$

and the predicted response at the stationary point (Y_0) is obtained from the following equation:

$$Y_0 = b_0 + \frac{1}{2} \sum_{i=1}^3 b_i x_i \quad (6)$$

where x_i is the co-ordinate of the stationary point in coded form. When the predicted yield (i.e., eqn. (6)) lies within the experimentally obtained values and eqn. (5) is validated, then the coordinates of the stationary point give the required optimum conditions.

Table 38 Analysis of Variance for the Silica Sand System Median Size Model Equa

Source	Sum of Squares	D.F.	Mean Square	Mean Sq. Rates
Constant	593.976	1		
Main Effect				
Speed	3.151	1	3.15	24.46
Pulp Density	13.506	1	13.51	104.82
Feed Size	0.016	1	0.016	0.12
Quadratic Order Effect				
Speed	0.378	1	0.378	2.93
Pulp Density	0.043	1	0.043	0.33
Feed Size	0.041	1	0.041	0.32
Total Sq. Terms	0.462	3	0.154	1.2
Interaction Effect				
Speed-Pulp Density	0.661	1	0.661	5.13
Speed-Feed Size	0.281	1	0.281	2.18
Pulp Density-Feed Size	0.031	1	0.031	0.24
Lack of Fit	0.469	5	0.094	0.5
Error	0.562	3	0.187	
Residual	1.031	8	0.129	
Total	613.12	18		

Table 39 Analysis of Variance for the Silica Sand System Energy Model Equation

Source	Sum of Squares	D.F.	Mean Square	Mean Sq. Rates
Constant	3764265	1		
Main Effect				
Speed	1016200	1	1016200	204.8
Pulp Density	399869.7	1	399569.7	80.59
Feed Size	0.35	1	0.35	
Quadratic Order Effect				
Speed	60643.86	1	0.378	12.22
Pulp Density	99470.84	1	0.043	20.05
Feed Size	18.37	1	0.041	0.004
<i>Total Sq. Terms</i>	<i>160133.07</i>	<i>3</i>	<i>53377.69</i>	<i>10.76</i>
Interaction Effect				
Speed-Pulp Density	127696.9	1	127696.9	25.74
Speed-Feed Size	5971.61	1	5971.61	1.2
Pulp Density-Feed Si	0.067	1	0.067	
Lack of Fit	29847.48	5	5969.5	1.82
Error	9847.74	3	3282.58	
<i>Residual</i>	<i>39695.22</i>	<i>8</i>	<i>4961.9</i>	
Total	5513831.92	18		

Table 40 Analysis of Variance for the Steel Shot System Median Size Model Equa

Source	Sum of Squares	D.F.	Mean Square	Mean Sq. Rates
Constant	374.467	1		
Main Effect				
Speed	0.076	1	0.076	1.26
Pulp Density	2.806	1	2.806	46.56
Feed Size	0.016	1	0.016	2.59
Quadratic Order Effect				
Speed	0.03	1		0.5
Pulp Density	1.967	1		32.64
Feed Size	0.023	1		0.38
<i>Total Sq. Terms</i>	<i>2.02</i>	<i>3</i>	<i>0.673</i>	<i>11.17</i>
Interaction Effect				
Speed-Pulp Density	0.061	1	0.061	1.01
Speed-Feed Size	0.061	1	0.061	1.01
Pulp Density-Feed Si	0.001	1	0.001	0.02
Lack of Fit	0.326	5	0.065	1.26
Error	0.156	3	0.052	
<i>Residual</i>	<i>0.482</i>	<i>8</i>	<i>0.0603</i>	
Total	379.99	18		

Table 41 Analysis of Variance for the Steel Shot System Energy Model Equation

Source	Sum of Squares	D.F.	Mean Square	Mean Sq. Rates
Constant	16507070	1		
Main Effect				
Speed	3093272	1	3093272	121.31
Pulp Density	2101036	1	2101036	82.4
Feed Size	12828.96	1	12828.96	0.5
Quadratic Order Effect				
Speed	396041.8	1		15.53
Pulp Density	340139.5	1		13.34
Feed Size	10.1	1		
<i>Total Sq. Terms</i>	<i>736191.4</i>	<i>3</i>	<i>245397.1</i>	<i>9.62</i>
Interaction Effect				
Speed-Pulp Density	131261.5	1	131261.5	5.15
Speed-Feed Size	41236.2	1	41236.2	1.62
Pulp Density-Feed Size	3384.2	1	3384.2	0.13
Lack of Fit	149401.29	5	29880.26	1.64
Error	54593.71	3	18197.9	
<i>Residual</i>	<i>203995</i>	<i>8</i>	<i>25499.38</i>	
Total	22830275.26	18		

The canonical forms of both the median size and specific energy models for the silica sand system are as follows:

$$d_{50} = 5.76 - 0.14X_1^2 - 0.09X_2^2 + 0.22X_3^2 \quad (7)$$

where the corresponding transformations are:

$$\begin{aligned} X_1 &= -0.55X_1 - 0.4X_2 + 0.73X_3 + 0.50 \\ X_2 &= 0.28X_1 + 0.74X_2 + 0.62X_3 - 3.12 \\ X_3 &= 0.78X_1 - 0.55X_2 + 0.29X_3 - 1.95 \end{aligned} \quad (8)$$

$$E = 454.89 - 10.29X_1^2 + 9.16X_2^2 + 127.59X_3^2 \quad (9)$$

with the transformation for X as

$$\begin{aligned} X_1 &= -0.51X_1 - 0.43X_2 + 0.74X_3 + 2.89 \\ X_2 &= 0.49X_1 + 0.57X_2 + 0.67X_3 + 1.85 \\ X_3 &= 0.71X_1 - 0.70X_2 + 0.08X_3 + 1.14 \end{aligned} \quad (10)$$

When the constants in eqns. (7 & 9) are compared with the experimental values in Table 37, it is observed that they lie within the experimental region. Hence, the coordinates of the center points should give the optimal conditions. Furthermore, since some of the coefficients in eqns. (7 & 9) are negative, the form of surfaces which they represent is a saddle or minimax. If this is confirmed by further tests, it implies that a range of optimal values exist for the parameters. The confirmatory test runs were made and are shown in the next section. The surfaces represented by eqns. (7 & 9) are attenuated along the X_2 axis since this has the smallest coefficient (in absolute value terms). Since the coefficient of X_3 is larger than the others both in eqns. (7 & 9), any movement from the center point towards the X_3 axis will result in a rapid improvement in the yield. For the silica sand system, the estimated optimum conditions for the median size are 3375 rpm, 44% solids and 44 mesh feed size while the corresponding values for the specific energy are 2204 rpm, 40% solids, and 323 mesh feed size. Since the surface we are dealing with here is a col, there are a range of feasible optimal conditions as indicated previously.

The canonical forms for both the median size and specific energy in the case of the steel shot system are as follows:

$$d_{50} = 4.39 - 0.03X_1^2 + 0.06X_2^2 + 0.28X_3^2 \quad (11)$$

with the transformation for X as

$$\begin{aligned} X_1 &= -0.68X_1 - 0.08X_2 + 0.73X_3 + 1.90 \\ X_2 &= 0.71X_1 + 0.17X_2 + 0.68X_3 - 0.85 \\ X_3 &= -0.18X_1 + 0.98X_2 - 0.05X_3 - 0.71 \end{aligned} \quad (12)$$

$$E = 1094.78 + 21.83X_1^2 + 101.93X_2^2 + 238.02X_3^2 \quad (13)$$

with the transformation for X in terms of the old variables as

$$\begin{aligned} X_1 &= 0.23X_1 + 0.04X_2 + 0.97X_3 + 2.65 \\ X_2 &= 0.57X_1 + 0.81X_2 - 0.17X_3 - 0.24 \\ X_3 &= 0.79X_1 - 0.59X_2 - 0.17X_3 + 1.17 \end{aligned} \quad (14)$$

On comparing the yield predicted at the center (constants in eqns. (11 & 13)) with the values in Table 37, it is observed that they lie within the experimental region. Since one of the coefficients in eqn. (11) is negative, the surface the equation represents is a saddle or col as mentioned previously. Hence, there is a range of optimum values. In the case of eqn. (13), the surface depicts a minimum as all the coefficients are positive. A higher improvement in the response can be obtained by making more tests, varying the feed size since the coefficient of the feed size is larger in both eqns. (11 & 13). One set of optimal conditions for the median size is as follows: 1975 rpm, 37% solids, and 54 mesh feed size. The corresponding optimum conditions for the specific energy are 1734 rpm, 38% solids, and 270 mesh feed size. Since the canonical equations have to be validated, and this was not done here, the optimum values given should be considered as estimates.

The optimal conditions found for both the median size and specific energy for a particular system differ from one another. The fact that the surfaces from which these conditions are estimated are saddle or minimax further complicate the issue as these are characterized by a range of optimum conditions. However, there is no doubt that the conditions which are suitable for optimizing the product particle size may not necessarily be good for the specific energy. Depending on the objective, either the product size or the specific energy may be optimized. Besides, it seems that when the product particle size is optimized, the specific energy is simultaneously constrained. In this manner, a better estimate of the required energy consumption can be obtained for scale-up purposes.

When the results in Table 37 are compared with those of the other three coals, a trend/pattern is observed. For the four coals involved in this work, the degree of fineness of the product particle size depicted by either the median size or d90 after wet stirred milling, correlates with the hardness or HGI. In other words, the higher the Hardgrove

Index, the finer the product particle size. The specific energy in contrast, does not tend to correlate with the hardness or HGI of the coal. Rather, the softer coal, depending on the properties of the associated impurities appears to consume more power. While this may initially appear to be a great surprise, the reasons for it are rather easy to grasp. In order to do this, one needs to look into such things as the properties/characteristics of the respective coal/impurities, the grinding environment, the mechanism of particle breakage in the mill, and how the grinding force is transmitted to the media.

For example, a soft coal is characterized by an initially high breakage rate and a correspondingly high specific surface area. In a wet grinding operation, the rapid increase in the specific surface area impacts the grinding environment by adsorbing free water molecules and consequently changes the slurry rheology. In instances where a coal contains clay minerals having water abstraction capability such as montmorillonite as in Pocahontas #3, the impact on the environment is further aggravated. The rheological changes result in closed packing of the grinding media thereby increasing the friction in the system. Unfortunately, the stirring mechanism and the driving motor in stirred mills are very sensitive to such changes. Since the pressure build-up in the grinding chamber tends to impair the rotation of the stirrer, the driving motor tends to draw more power to overcome the friction or to increase the shearing action. A point can be reached where the movement of the stirrer is hampered such as the formation of a very thick paste. The power utilized in the above manner reflected in the specific energy thus inflating the value out of proportion. Therefore, a significant fraction of the specific energy obtained for the soft coals is actually used to overcome friction, or simply put, wasted.

Verification of Process Parameters

We had reported optimum operating conditions as determined by canonical analysis for Illinois #6 coal in the previous section. These optimum conditions refer to agitator speed, percent of solids and coal particle sizes. Unfortunately, some of the conditions were outside the feasible region of experimental values. However, we decided to conduct experimental verification using the nearest feasible value. For example, agitator speed (3375 RPM) and coal particle sizes (44 mesh, 323 mesh, 54 mesh, and 270 mesh) were substituted using appropriate values.

Table 42 shows the comparison of predicted values and experimental responses (specific energies, product sizes) for each of sand and steel shot system. It is clear from the data that the agreement among product sizes is far superior than specific energies. Note that optimized value (X3) is single particle size which is different from the one actually used in the experiments which contain range of particle sizes. This analysis shows that energy consumption is more sensitive to particle size than median product size.

F. Continuous Grinding Tests

1. Sand Media

As indicated in the batch tests, a small grinding chamber similar to that used in the batch tests but fitted with inlet and discharge openings was adopted. A variable speed Masterflex peristaltic pump was placed between the mixing tank, water tank and the grinding chamber inlet port and connected by a system of tubing, as shown in figure 8. The small size of the grinding chamber necessitates the use of a relatively low feed rate in order to keep the residence time of the particles in the mill at a reasonable level. Evidently, this is not enough to ensure that the desired very fine product can be obtained. Hence slurries have to be passed through the mill a number of times. Thereby simulating a grinding circuit consisting of a number of mills in series. Depending on the hardness of the coal, between 3 to 4 passes are sufficient to obtain very fine products as depicted by Tables 43-46. The harder the coal, the higher the number of passes required. This is of course influenced by such factors as the initial feed particle size, pulp density, feed rate and stirring speed.

The fact that no media retaining device is employed in the discharge port placed some limitations on the operation. The decision to use an open discharge port was reached as severe clogging problems prevented the use of sieve as a retaining device. Even without the retaining

Table 42 Comparison of Predicted Optimized Responses
with Experimental Results for Illinois #6 Coal

Test Conditions				Energy Consumption (KWH/Ton)		Product Size (D50, μ)	
Media	RPM (X1)	% Solids (X2)	Feed Size in Mesh (X3)	Predicted	Expl.	Predicted	Expl.
Sand	3280 (+2)	44 (1.4)	50X60 (+2)			5.81	5.3
Sand	2204 (-0.24)	40 (+1)	270X325 (-2)	206.75	170.21		
Steel	1975 (-0.81)	37 (-0.7)	50X60 (+2)			3.83	3.9
Steel	1734 (-1.41)	38 (+0.8)	200X325 (-2)	131.77	314.12		

device, the grinding operation has to be carried out in such a manner that most of the media remain in the grinding chamber for it to be effective. This was achieved by exploiting gravitational force or specific gravity difference to effect the separation of coal slurry from the media inside the grinding chamber. The implication is that the mill capacity has to be compromised as less than optimal levels of such factors as feed particle size, feed flow rate and initial solids concentration have to be employed.

With the above restrictions in mind, we set out to explore the range in which the continuous grinding circuit can be used to produce products consisting of very fine particles. In the present investigation, two polydispersed feed with a size designation of minus 50 mesh and minus 100 mesh were chosen as well as initial solids concentration in the range of 20 to 40 weight percent. The term initial solids concentration is used to denote the starting pulp density in the mixing tank. The starting solids concentration is emphasized because the operating procedure adopted results in a slight dilution of the commencement of grinding.

The procedure involves measuring the desired amount of dry coal and water and mixing in a stirred tank to give the pulp density of interest. Then the stirring mechanism is set in place, the required amount of grinding media measured (which for silica sand is chosen as 250 g) and placed in the mill. Thereafter the mill cover is locked, the water valve is opened and the pump is switched on. Then the mill cover and tubes are checked for leakage and the pump speed is adjusted. After the check up, the grinding mill motor is switched on, the water valve is closed while the slurry valve is opened and further adjustments are on the the pump speed. This procedure appears to be essential for a smooth running of the continuous grinding system. However, when a small volume of slurry is used, a significant dilution may result.

For the four coals employed in this work, it was not possible to effectively grind the minus 50 mesh feed even at the lowest solids concentration range tried. The reason for this is the low feed rate which makes it impossible to obtain a uniform flow as the coarse particles in the feed tend to settle down and form sediment in either the tubing system or the grinding chamber. Besides, only moderate levels of solids concentration could be employed as high solids concentration are also fraught with sedimentation problem. Attempts to increase the flow rate resulted in the grinding media being taken out of the mill together with the slurry. As a result of these limitations posed by the instrument, further tests were restricted to using minus 100 mesh feed size and moderate levels of feed rate and pulp density.

Some of the results obtained are given in Tables 43-46 for the different coals used. It can be seen from the tables that the softest coal (Pocahontas #3 in this case) requires about 2 or 3

passes in order to obtain very fine product while the harder coals would require 4 or more passes. The number of passes required for the harder coals can be reduced either by increasing the residence time of the slurry in the mill by decreasing the feed rate or preferably by increasing the stirring speed. Both of these actions will inevitably lead to a slight increase in the media wear. The media wear observed in grinding Pocahontas #3 in three cycles was 1.3% while the corresponding values for grinding both Illinois #6 and Black Creek coals in four cycles were 0.5% and 1.5% respectively. The above media wear values for the respective coals reflect more about the flow characteristics of the various coal slurries as opposed to the coals hardness. The media wear was determined from the difference in the mass of the media after grinding. The media wear rate is surprisingly quite low. It should, however, be emphasized that the wear value is greatly dependent on the slurry flow characteristics or rheology. This is the reason why the media wear obtained in grinding Pocahontas #3 which is soft in three cycles is of the same magnitude as that observed for Black Creek coal. For the former, most of the media wear occurred presumably during the last cycle of grinding as evident from the change in the sound produced by the grinding chamber.

2. Steel Media

As indicated in the previous section, continuous grinding tests using silica sand as grinding media had been carried out under selected conditions. Continuous grinding tests using steel shots were made during this quarter. The tests were carried out in the same grinding circuit, under similar test conditions in order to compare the tests results.

In the steel media continuous grinding tests, 173 grams coal and 713.9 grams steel shots were employed in each test to match the volume of the sand media used in the former tests. We decided to use only minus 100 mesh of the coal feed in these continuous tests because coarser feeds might have caused problems as pointed out in the sand grinding continuous tests. 25% starting pulp density was used during these tests. The weight of steel shots was measured before and after grinding tests to calculate to the consumption of the grinding media. For all of the four coals, four passes were carried out to produce fine grinding products and the results were compared with those of sand media continuous grinding tests.

The results of steel media continuous tests are given in Tables 47-50. The media wear measured in the tests for Black Creek, Illinois #6, Pittsburgh #8 coals were 0.24%, 0.24%, and 0.20% respectively.

If we compare the data of Tables 43-46 and Tables 47-50, we can see that the size distributions of the ground products using different grinding media for same coal are quite similar. The amount of coarser particles (>16 micron) for steel media ground products is smaller, while the

Table 43 The product size distributions of minus 100 mesh Pocahontas #3 coal ground in a continuous mode at 2500 rpm, 25% solids and a flow rate of 25 ml/min.

Particle Sizes (μm)	Cumulative Weight Percent Passing		
	1st pass	2nd pass	3rd pass
96	100.0	100.0	100.0
64	98.4	100.0	100.0
48	96.8	100.0	100.0
32	92.7	100.0	100.0
24	90.5	100.0	100.0
16	82.3	97.3	99.6
12	72.9	93.5	99.2
8	56.7	79.1	92.4
6	44.4	65.6	84.9
4	29.0	43.8	62.9
3	20.5	31.6	47.8
2	12.8	19.7	29.4
1.5	8.0	12.8	19.5
1	6.3	10.0	14.9

Table 44 The product size distributions of minus 100 mesh Pittsburgh #8 coal ground in a continuous mode at 2500 rpm, 26% solids and a flow rate of 45 ml/min.

Particle Sizes (μm)	Cumulative Weight Percent Passing			
	1st pass	2nd pass	3rd pass	4th pass
192	100.0	100.0	100.0	100.0
128	99.0	100.0	100.0	100.0
96	96.0	100.0	100.0	100.0
64	88.6	96.9	99.6	99.9
48	85.6	96.9	99.2	99.9
32	76.2	91.9	98.1	99.9
24	68.1	87.4	97.0	99.9
16	53.3	72.9	87.4	93.8
12	40.2	58.2	75.1	84.3
8	26.3	39.0	52.2	61.9
6	18.5	28.2	38.0	45.9
4	12.0	18.2	23.6	28.0
3	8.6	13.2	17.2	20.1
2	6.0	9.1	11.7	13.6
1.5	3.9	5.9	7.7	9.0
1	3.2	4.7	6.1	7.1

Table 45 The product size distributions of minus 100 mesh Illinois #6 coal ground in a continuous mode at 2500 rpm, 24% solids and a flow rate of 40 ml/min.

Particle Sizes (μm)	Cumulative Weight Percent Passing			
	1st pass	2nd pass	3rd pass	4th pass
192	100.0	100.0	100.0	100.0
128	99.0	100.0	100.0	100.0
96	96.1	100.0	100.0	100.0
64	89.9	98.6	99.6	99.8
48	87.5	97.3	99.2	99.6
32	78.8	91.8	97.2	99.3
24	71.7	86.4	95.6	99.1
16	58.3	70.1	83.5	90.8
12	45.7	55.0	68.8	78.5
8	31.6	36.8	46.8	55.3
6	22.8	27.1	34.0	40.3
4	15.2	18.2	21.9	25.2
3	11.1	13.5	16.3	18.5
2	7.5	9.1	10.9	12.0
1.5	4.3	5.3	6.4	7.1
1	3.3	4.1	4.8	5.4

Table 46 The product size distributions of minus 100 mesh Black Creek coal ground in a continuous mode at 2500 rpm, 26% solids and a flow rate of 48 ml/min.

Particle Sizes (μm)	Cumulative Weight Percent Passing			
	1st pass	2nd pass	3rd pass	4th pass
192	100.0	100.0	100.0	100.0
128	98.5	99.9	100.0	100.0
96	94.1	99.7	100.0	100.0
64	85.5	96.9	99.2	99.8
48	82.2	95.8	98.5	99.6
32	70.1	89.7	94.9	97.6
24	60.9	83.4	92.7	97.0
16	46.2	68.6	81.0	88.8
12	33.9	53.7	67.3	77.0
8	21.8	35.6	45.3	54.4
6	15.2	25.1	31.9	38.6
4	9.9	15.8	19.2	22.8
3	6.9	11.1	13.6	16.0
2	4.6	7.5	9.0	10.6
1.5	2.8	4.6	5.6	6.7
1	2.2	3.7	4.4	5.3

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Table 47 The product size distributions of minus 100 mesh Pocahontas #3 coal ground in a continuous mode at 2500 rpm, 25% solids and a flow rate of 43 ml/min.

Particle Sizes (μm)	Cumulative Weight Percent Passing			
	1st pass	2nd pass	3rd pass	4th pass
192	100.0	100.0	100.0	100.0
128	100.0	100.0	100.0	100.0
96	99.9	100.0	100.0	100.0
64	96.0	99.8	100.0	100.0
48	94.5	99.8	100.0	100.0
32	88.3	99.8	100.0	100.0
24	82.9	99.7	100.0	100.0
16	69.6	97.2	96.9	97.6
12	55.8	93.3	93.2	96.9
8	38.8	80.3	80.2	85.7
6	28.0	67.2	68.2	75.9
4	17.5	44.9	46.7	52.8
3	12.0	31.8	33.8	38.8
2	7.7	19.3	20.4	22.8
1.5	4.9	12.5	13.1	14.7
1	3.9	9.7	10.1	11.2

Table 48 The product size distributions of minus 100 mesh Pittsburgh #8 coal ground in a continuous mode at 2500 rpm, 26% solids and a flow rate of 62 ml/min.

Particle Sizes (μm)	Cumulative Weight Percent Passing			
	1st pass	2nd pass	3rd pass	4th pass
192	100.0	100.0	100.0	100.0
128	99.9	100.0	100.0	100.0
96	99.7	100.0	100.0	100.0
64	94.6	99.3	99.9	99.8
48	92.1	98.7	99.8	99.7
32	82.8	97.4	99.8	99.7
24	68.1	96.8	99.8	99.7
16	56.7	88.1	93.6	97.8
12	41.5	75.6	84.5	89.7
8	26.1	53.3	62.5	71.5
6	18.1	38.1	46.3	54.0
4	11.8	22.7	27.1	32.5
3	8.5	15.9	18.9	22.0
2	6.1	10.8	12.5	14.6
1.5	3.9	7.1	8.3	9.5
1	3.2	5.7	6.6	7.6

Table 49 The product size distributions of minus 100 mesh Illinois #6 coal ground in a continuous mode at 2500 rpm, 24% solids and a flow rate of 56 ml/min.

Particle Sizes (μm)	Cumulative Weight Percent Passing			
	1st pass	2nd pass	3rd pass	4th pass
192	100.0	100.0	100.0	100.0
128	100.0	100.0	100.0	100.0
96	100.0	100.0	100.0	100.0
64	97.9	99.6	99.9	100.0
48	97.3	99.3	99.8	100.0
32	92.8	98.9	99.6	100.0
24	86.8	97.3	99.3	100.0
16	70.1	88.3	92.3	96.1
12	53.1	73.8	80.1	86.5
8	33.2	50.8	57.6	66.1
6	22.8	35.8	41.6	49.3
4	14.7	22.3	25.4	30.4
3	10.8	16.2	18.3	21.5
2	7.5	10.8	12.3	13.6
1.5	4.5	6.2	7.2	7.6
1	3.5	4.7	5.5	5.6

Table 50 The product size distributions of minus 100 mesh Black Creek coal ground in a continuous mode at 2500 rpm, 26% solids and a flow rate of 62 ml/min.

Particle Sizes (μm)	Cumulative Weight Percent Passing			
	1st pass	2nd pass	3rd pass	4th pass
192	100.0	100.0	100.0	100.0
128	98.9	100.0	100.0	100.0
96	95.9	100.0	100.0	100.0
64	88.1	98.8	99.4	99.9
48	84.9	98.4	98.9	99.8
32	74.1	96.3	97.7	99.7
24	65.4	93.9	96.9	99.5
16	49.7	83.8	88.6	93.8
12	36.1	69.4	76.2	83.7
8	22.3	46.4	53.3	61.9
6	14.9	31.6	37.3	44.5
4	9.2	17.9	20.8	25.0
3	6.3	12.2	14.1	16.7
2	4.2	8.3	9.3	10.8
1.5	2.5	5.3	5.9	6.9
1	2.1	4.2	4.7	5.4

ultra-fine part (< 2 micron for example,) were almost the same. That means that the sand media grinding produced relatively more finer particles compared with steel media grinding. This phenomenon might be due to the different grinding mechanisms involved in these two systems.

G. Fracture Mechanics Tests

In these tests, four monodispersed and one polydispersed samples prepared from each of the four coal types were used. The so-called uniaxial testing machine manufactured by Tinius Olsen was used to apply the required load on the sample which was placed in a cell made for this purpose.

Preliminary test runs were first made to determine both the amount of sample required to obtain a cylindrical cake of about 4 inches in height and a load which would yield a cake of adequate strength.

It was decided from the trial data to use 240 grams from each of the dry coal samples. In order to obtain a cake following the application of load, an amount of water varying between 34 to 80 ml was used to increase the moisture content of the sample. The variation in the amount of water required is due to the degree of fineness of the particles which make up the samples. A constant pressure of about 12,700 psi was chosen for the test and applied for a duration of one hour. Cylindrical cakes having a diameter of 2 inches and a height varying between 4 to $4\frac{1}{2}$ inches were obtained depending on the coal hardness and initial particle size.

The wet cylindrical cores were weighed and allowed to dry in air for a number of days before being subjected to further uniaxial compression tests. In these tests series, small increments of load were applied on each of the core and the strain release was measured using a dual-sensor strain transducer (supplied by the Measurement Technology Inc.), connected to two strain indicators model P 3500 made by the Measurement Group. The vertical and horizontal strains were measured in this manner when a core was subjected to stress. The results of these tests are given in Tables 51-70. It can be seen that there is a strong correlation between the rate of strain release and the property or hardness of the coal. The rate of strain release seems to increase with the hardness of coal. In other words, the harder the coal, the lower the amount of stress a cake can withstand before failure. A similar inference appears to be true for the initial particle size of the sample used to make a cake. That is, the smaller the particle size, the higher the stress a cake made up of such particles can withstand.

Table 51 The stress, strain and Poisson ratio of a compressed cake made from a 50 x 60 mesh size Pocahontas #3 coal.

Stress (psi)	Strain		Poisson Ratio
	Vertical	Horizontal	
3.18	570.96		
12.73	1478.88		
19.10	2190.24		
25.47	2995.20		
31.83	3912.48		
38.20	4661.28		
50.93	6430.32		
57.30	7441.20	40.48	5.44×10^{-3}
63.66	8424.00	60.72	7.21×10^{-3}
70.03	9266.40	65.78	7.10×10^{-3}
82.76	11316.24	80.96	7.15×10^{-3}
89.13	11952.72	101.20	8.47×10^{-3}
101.86	13478.40	126.50	9.39×10^{-3}
108.23	14189.76	136.62	9.63×10^{-3}
114.59	14882.40	151.80	10.20×10^{-3}
120.96	15715.44	166.98	10.63×10^{-3}
127.32	16417.44	182.16	11.10×10^{-3}
133.69	17035.20	212.52	12.48×10^{-3}
140.06	17690.40	227.70	12.87×10^{-3}
146.42	18439.20	242.88	13.17×10^{-3}
152.79	19253.52	263.12	13.67×10^{-3}
159.16	19740.24	298.54	15.12×10^{-3}
165.52	20769.84	313.72	15.11×10^{-3}
171.89	21556.08	354.20	16.43×10^{-3}

Table 52 The stress, strain and Poisson ratio of a compressed cake made from a 60 x 100 mesh size Pocahontas #3 coal.

Stress (psi)	Strain		
	Vertical	Horizontal	Poisson Ratio
15.92	1123.20		
47.75	5260.32	25.30	4.81×10^{-3}
63.66	7141.68	30.36	4.25×10^{-3}
79.58	8882.64	45.54	5.13×10^{-3}
95.49	10361.52	60.72	5.86×10^{-3}
127.32	13384.80	101.20	7.56×10^{-3}
143.24	14798.16	116.38	7.87×10^{-3}
175.07	17493.84	166.98	9.55×10^{-3}
206.90	19787.04	222.64	11.25×10^{-3}
238.73	22155.12	283.36	12.79×10^{-3}
254.65	23156.64	318.78	13.77×10^{-3}
286.48	25637.04	414.92	16.18×10^{-3}
318.31	27144.00	516.12	19.01×10^{-3}

Table 53 The stress, strain and Poisson ratio of a compressed cake made from a 150 x 200 mesh size Pocahontas #3 coal.

Stress (psi)	Strain		Poisson Ratio
	Vertical	Horizontal	
15.92	1740.96		
31.83	3238.56	10.12	3.13×10^{-3}
47.75	4286.88	25.30	5.90×10^{-3}
63.66	5840.64	30.36	5.20×10^{-3}
95.49	9126.00	50.60	5.55×10^{-3}
127.32	12055.68	80.96	6.72×10^{-3}
159.16	14854.32	121.44	8.18×10^{-3}
190.99	17316.00	161.92	9.35×10^{-3}
222.82	19787.04	202.40	10.23×10^{-3}
254.65	21902.40	258.06	11.78×10^{-3}
286.48	24204.96	318.78	13.17×10^{-3}
318.31	29016.00	374.44	12.91×10^{-3}

Table 54 The stress, strain and Poisson ratio of a compressed cake made from a 200 x 270 mesh size Pocahontas #3 coal.

Stress (psi)	Strain		Poisson Ratio
	Vertical	Horizontal	
15.92	1460.16		
47.75	3762.42	10.12	2.69×10^{-3}
63.66	4754.88	20.24	4.26×10^{-3}
79.58	5850.00	30.36	5.19×10^{-3}
111.41	8030.88	40.48	5.04×10^{-3}
159.16	11222.64	65.78	5.86×10^{-3}
190.99	13338.00	80.96	6.07×10^{-3}
238.73	16239.60	116.38	7.17×10^{-3}
286.48	18851.04	166.98	8.86×10^{-3}
334.23	21378.24	217.58	10.18×10^{-3}
381.97	23652.72	273.24	11.55×10^{-3}
413.80	24738.48	328.90	13.30×10^{-3}
445.63	26563.68	354.20	13.33×10^{-3}
477.47	28491.84	435.16	15.27×10^{-3}

Table 55 The stress, strain and Poisson ratio of a compressed cake made from a minus 60 mesh size Pocahontas #3 coal.

Stress(psi)	Strain		Poisson Ratio
	Vertical	Horizontal	
15.92	2742.48		
47.75	5802.20	15.18	2.62×10^{-3}
79.49	10080.72	60.72	6.02×10^{-3}
111.41	13572.00	121.44	8.95×10^{-3}
143.24	16623.36	172.04	10.35×10^{-3}
159.16	17933.76	202.40	11.29×10^{-3}
175.07	19281.60	237.82	12.33×10^{-3}
190.99	20554.56	283.36	13.79×10^{-3}
206.90	21855.60	328.90	15.05×10^{-3}
222.82	23194.08	379.50	16.36×10^{-3}
238.73	24654.24	445.28	18.06×10^{-3}

Table 56 The stress, strain and Poisson ratio of a compressed cake made from a 50 x 60 mesh size Pittsburgh #8 coal.

Stress (psi)	Strain		Poisson Ratio
	Vertical	Horizontal	
15.92	1488.24		
31.83	3060.72		
47.75	4006.08	15.18	3.79×10^{-3}

Table 57 The stress, strain and Poisson ratio of a compressed cake made from a 60 x 100 mesh size Pittsburgh #8 coal.

Stress (psi)	Strain		Poisson Ratio
	Vertical	Horizontal	
6.37	898.51		
19.10	2517.84		
25.47	3238.56		
38.20	5335.20	10.12	1.90×10^{-3}
44.56	6982.56	20.24	2.90×10^{-3}
57.30	10969.92	80.96	7.38×10^{-3}
63.66	11671.92	121.44	10.40×10^{-3}
76.39	12589.20	253.00	20.10×10^{-3}
89.13	17821.44	379.50	21.30×10^{-3}
101.86	21808.80	379.5	17.40×10^{-3}

Table 58 The stress, strain and Poisson ratio of a compressed cake made from a 150 x 200 mesh size Pittsburgh #8 coal.

Stress (psi)	Strain		Poisson Ratio*
	Vertical	Horizontal*	
6.37	505.44		
19.10	1647.36		
31.83	3369.60		
44.56	5035.68	* Could not record the readings.	
50.93	5821.92		
57.30	6449.04		
63.66	7066.80		
70.03	7684.56		
82.76	9294.48		

Table 59 The stress, strain and Poisson ratio of a compressed cake made from a 150 x 200 mesh size Pittsburgh #8 coal.

Stress (psi)	Strain		
	Vertical	Horizontal	Poisson Ratio
15.92	926.64		
47.75	3032.64		
79.58	6121.44	10.12	1.65×10^{-3}
95.49	8161.92	25.30	3.10×10^{-3}
111.41	10146.24	60.72	5.98×10^{-3}
127.32	12205.44	91.08	7.46×10^{-3}
143.24	14358.24	131.56	9.16×10^{-3}
159.16	16670.16	192.28	11.53×10^{-3}
175.07	18925.92	278.30	14.71×10^{-3}
190.99	20872.80	369.38	17.70×10^{-3}

Table 60 The stress, strain and Poisson ratio of a compressed cake made from a minus 60 mesh size Pittsburgh #8 coal.

Stress (psi)	Strain		Poisson Ratio
	Vertical	Horizontal	
6.37	1160.64		
25.47	2826.72		
31.83	3538.08		
44.56	5129.28	10.12	1.97×10^{-3}
57.30	6963.84	30.36	4.36×10^{-3}
70.03	9051.12	50.60	5.59×10^{-3}
82.76	11831.04	70.84	5.99×10^{-3}
95.49	14732.64	101.20	5.87×10^{-3}
108.23	18158.40	131.56	7.25×10^{-3}
120.96	22136.40	207.46	9.37×10^{-3}
133.69	26544.96	253.00	9.53×10^{-3}
146.42	36073.44	136.62	3.79×10^{-3}
159.16	42896.88	126.20	2.95×10^{-3}
165.52	45826.56	116.38	2.54×10^{-3}

Table 61 The stress, strain and Poisson ratio of a compressed cake made from a 50 x 60 mesh size Illinois #6 coal.

Stress (psi)	Strain		Poisson Ratio
	Vertical	Horizontal	
6.37	4558.32		
12.73	7197.84	35.42	7.77×10^{-3}
19.10	10735.92	65.78	6.13×10^{-3}
25.47	13824.72	131.56	9.52×10^{-3}
31.83	17082.00	227.7	13.30×10^{-3}

Table 62 The stress, strain and Poisson ratio of a compressed cake made from a 60 x 100 mesh size Illinois #6 coal.

Stress(psi)	Strain		Poisson Ratio
	Vertical	Horizontal	
6.37	5110.56		
12.73	5335.20	15.18	2.85×10^{-3}
19.10	9921.60	35.42	3.57×10^{-3}
25.47	12467.52	50.60	4.06×10^{-3}
31.83	16351.92	80.96	4.95×10^{-3}
38.20	19974.24	126.50	6.33×10^{-3}
44.56	23783.76	227.70	9.57×10^{-3}
50.93	26994.24	288.42	10.69×10^{-3}
57.30	30026.88	348.56	12.81×10^{-3}
63.66	33546.24	480.70	14.33×10^{-3}
70.03	37093.68	571.78	15.41×10^{-3}
76.39	41052.96	688.16	16.76×10^{-3}

Table 63 The stress, strain and Poisson ratio of a compressed cake made from a 150 x 200 mesh size Illinois #6 coal.

Stress (psi)	Strain		Poisson Ratio
	Vertical	Horizontal	
15.92	2208.96		
31.83	5054.40	25.30	5.01×10^{-3}
47.75	8555.04	55.66	6.51×10^{-3}
63.66	12963.60	111.32	8.59×10^{-3}
79.58	18439.20	202.40	10.98×10^{-3}
95.49	23212.80	333.96	14.39×10^{-3}
111.41	27892.40	480.70	17.23×10^{-3}
127.32	32198.40	672.98	20.90×10^{-3}
143.24	34856.64	890.56	25.55×10^{-3}

Table 64 The stress, strain and Poisson ratio of a compressed cake made from a 200 x 270 mesh size Illinois #6 coal.

Stress (psi)	Strain		Poisson Ratio
	Vertical	Horizontal	
6.37	1956.24		
12.73	3388.32		
25.47	5990.40		
44.56	8424.00	30.36	3.60×10^{-3}
57.30	9912.24	50.60	5.11×10^{-3}
63.66	10801.44	60.72	5.62×10^{-3}
82.76	14657.76	80.96	5.52×10^{-3}
89.13	15724.80	91.08	5.79×10^{-3}
95.49	17128.80	111.32	6.50×10^{-3}
108.23	19936.80	151.80	7.61×10^{-3}
127.32	25234.56	263.12	10.43×10^{-3}
140.06	28744.56	394.68	13.73×10^{-3}
152.79	34070.40	617.32	18.12×10^{-3}

Table 65 The stress, strain and Poisson ratio of a compressed cake made from a minus 60 mesh size Illinois #6 coal.

Stress (psi)	Strain		Poisson Ratio
	Vertical	Horizontal	
6.37	2227.68		
19.10	5035.68	30.36	6.03×10^{-3}
31.83	8480.16	60.72	7.16×10^{-3}
44.56	12823.20	126.50	9.87×10^{-3}
57.30	16791.84	227.70	13.56×10^{-3}
63.66	18897.84	293.48	15.53×10^{-3}
76.39	22538.88	430.10	19.08×10^{-3}
89.13	25646.40	617.32	24.07×10^{-3}
95.49	26956.80	708.40	26.28×10^{-3}
101.86	28360.80	885.50	31.22×10^{-3}

Table 66 The stress, strain and Poisson ratio of a compressed cake made from a 50 x 60 mesh size Black Creek coal.

Stress (psi)	Strain		Poisson Ratio
	Vertical	Horizontal	
15.92	12055.68	75.90	6.30×10^{-3}
31.83	22464.00	318.78	14.19×10^{-3}

Table 67 The stress, strain and Poisson ratio of a compressed cake made from a 60 x 100 mesh size Black Creek coal.

Stress (psi)	Strain		Poisson Ratio
	Vertical	Horizontal	
6.37	2040.48		
12.73	4680.00	15.18	2.24×10^{-3}
19.10	8611.20	75.90	8.81×10^{-3}
25.47	13665.60	151.80	11.11×10^{-3}
31.83	17849.52	268.18	15.02×10^{-3}
38.20	21556.08	379.50	17.61×10^{-3}
44.56	24672.96	506.00	20.51×10^{-3}
50.93	27087.84	667.92	24.66×10^{-3}

Table 68 The stress, strain and Poisson ratio of a compressed cake made from a 150 x 200 mesh size Black Creek coal.

Stress (psi)	Strain		Poisson Ratio
	Vertical	Horizontal	
15.92	3556.80	10.12	2.85×10^{-3}
31.83	8161.92	30.36	3.72×10^{-3}
47.75	13235.04	80.96	6.12×10^{-3}
63.66	17933.76	177.10	9.88×10^{-3}
79.58	23802.48	313.72	13.18×10^{-3}
95.49	28416.96	485.76	17.09×10^{-3}
111.41	31889.52	629.84	26.02×10^{-3}

Table 69 The stress, strain and Poisson ratio of a compressed cake made from a 200 x 270 mesh size Black Creek coal.

Stress (psi)	Strain		Poisson Ratio
	Vertical	Horizontal	
15.92	1310.40		
31.83	2995.20		
47.75	5353.92	20.24	3.78×10^{-3}
63.66	8115.12	40.48	4.99×10^{-3}
79.58	11671.92	75.90	6.50×10^{-3}
95.49	15369.12	126.50	8.23×10^{-3}
111.41	19478.16	197.34	10.13×10^{-3}
127.32	24017.76	323.84	13.48×10^{-3}

Table 70 The stress, strain and Poisson ratio of a compressed cake made from a minus 60 mesh size Black Creek coal.

Stress (psi)	Strain		Poisson Ratio
	Vertical	Horizontal	
6.37	1581.84		
12.73	3818.88	10.12	2.65×10^{-3}
19.10	6177.60	25.30	4.10×10^{-3}
25.47	8255.52	40.48	4.90×10^{-3}
31.83	10670.40	60.72	5.69×10^{-3}
38.20	13431.60	101.20	7.53×10^{-3}
44.56	16604.64	151.80	9.14×10^{-3}
50.93	18794.88	212.52	11.31×10^{-3}
57.30	20854.08	263.12	12.62×10^{-3}
63.66	23166.00	333.96	14.42×10^{-3}
70.03	24785.28	495.88	20.01×10^{-3}
76.39	26685.36	607.20	22.75×10^{-3}

The cakes made with the softest coal (Pocahontas #3) tend to exhibit greater resistance to stress. This feature could presumably be attributed to the presence of a significant amount of clay in the coal which have been mentioned in previous reports. While these observations reflect the characteristics expected of the respective cakes, any inference as regards the actual breakage behaviors of the particles require caution.

The particle size distributions resulting from the application of load used to compress the coal samples are given on the basis of the initial particle sizes in Tables 71-75. It can be seen from the above tables that an extensive breakage of over 50% occurred in all the feed sizes range used. The high values in Table 75 is partly due to the different sizing device used for the measurement of the particles. While sieves were used for evaluating the particle size distributions given in Tables 71-74, the data in Table 75 were determined using Cilas Granulometre because of the very fine nature of the particles. In general, the amount of material broken out of the initial (feed) size intervals appears to be higher for the soft coals compared with the hard coals. However, the hard coals seem to produce a larger amount of fines. More tests would be made at a higher pressure to ascertain whether the enumerated patterns would be maintained.

1. Effect of Compaction Pressure

In the previous section, the conditions of fracture mechanics tests were described in detail. The tests carried out in those tests were for coal samples prepared at constant pressure of about 12,700 psi applied for a duration of one hour. In order to understand the effect of initial compaction pressure on the fracture mechanism and to compare the results of different conditions, more tests were carried out for Illinois #6 coal and Pocahontas #3 coal at different conditions. We used 19,100 psi and 25,500 psi pressure for a duration of 10 minutes in these tests. The other conditions were the same.

The results of the fracture mechanics tests are given in terms of stress, strain, and Poisson ratio, which are shown in Tables 76-81.

The cakes made with the softest coal (Pocahontas #3) tend to exhibit greater resistance to stress. This feature could presumably be attributed to the presence of a significant amount of clay or other mineral matter in the coal. This is also true for the coarser coal (50X60 mesh) cylinders made at higher pressure. If we compare Tables 76, 77 and Tables 79, 80, we can see that the pressure that caused the coal cores to crackdown for Pocahontas #3 coal is greater than those for Illinois #6 coal. The vertical strains for the former are greater as well. For finer coals, however, this is not true (table 78, table 81). The reason needs to be studied further. If we compare the Tables 76-81 with table 51, table 61 and table 69, we find that the higher the pressure applied on

Table 71 The particle size distributions resulting from the compression of 50 x 60 mesh coal at 12,700 psi and the maximum stress, strain and Poisson ratio exhibited by the respective dry cakes.

Size (mesh)	Cumulative Weight Percent Passing			
	Black Creek	Illinois #6	Pittsburgh #8	Pocahontas #3
50	100.0	100.0	100.0	100.0
60	65.1	69.88	83.52	96.97
100	35.74	35.36	45.72	67.31
150	25.46	23.19	32.13	50.46
200	17.57	14.34	20.32	31.93
270	13.21	9.35	11.52	11.21
Max σ (psi)	31.83	31.83	47.75	171.89
Max ϵ_v	22464	17082	4006.08	21556.08
Poisson Ratio	14.19×10^{-3}	13.33×10^{-3}	3.79×10^{-3}	16.43×10^{-3}

Table 72 The particle size distributions resulting from the compression of 60 x 100 mesh coal at 12,700 psi and the maximum stress, strain and Poisson ratio exhibited by the respective dry cakes.

Size (mesh)	Cumulative Weight Percent Passing			
	Black Creek	Illinois #6	Pittsburgh #8	Pocahontas #3
60	100.0	100.0	100.0	100.0
100	54.62	60.87	63.04	77.65
150	33.91	35.78	40.26	58.13
200	21.81	22.08	22.44	26.30
270	14.93	15.42	11.43	6.70
Max σ (psi)	50.93	76.39	101.86	318.31
Max ϵ_v	27087.84	41052.96	21808.80	27144.0
Poisson Ratio	24.66×10^{-3}	16.76×10^{-3}	17.40×10^{-3}	19.01×10^{-3}

Table 73 The particle size distributions resulting from the compression of 150 x 200 mesh coal at 12,700 psi and the maximum stress, strain and Poisson ratio exhibited by the respective dry cakes.

Size	Cumulative Weight Percent Passing			
(mesh)	Black Creek	Illinois #6	Pittsburgh #8	Pocahontas #3
150	100.0	100.0	100.0	100.0
200	60.58	45.60	39.56	55.23
270	26.69	25.25	17.48	18.44
Max σ (psi)	111.41	143.24	82.76	318.31
Max ϵ_v	31889.52	34856.64	9294.48	29016
Poisson Ratio	26.02×10^{-3}	25.55×10^{-3}	-----	12.91×10^{-3}

Table 74 . The particle size distributions resulting from the compression of minus 60 mesh coal at 12,700 psi and the maximum stress, strain and Poisson ratio exhibited by the respective dry cakes.

Size	Cumulative Weight Percent Passing			
(mesh)	Black Creek	Illinois #6	Pittsburgh #8	Pocahontas #3
60	100.0	100.0	100.0	100.0
100	74.93	72.19	77.70	80.46
150	54.85	51.69	54.99	62.39
200	37.01	33.38	21.67	28.26
270	22.72	18.86	9.90	8.34
Max σ (psi)	76.39	101.86	165.52	238.73
Max ϵ_v	26685.36	28360.80	45826.56	24654.24
Poisson Ratio	22.75×10^{-3}	31.22×10^{-3}	2.54×10^{-3}	18.06×10^{-3}

Table 75 The particle size distributions resulting from the compression of 200 x 270 mesh coal at 12,700 psi and the maximum stress, strain and Poisson ratio exhibited by the respective dry cakes.

Size (μm)	Cumulative Weight Percent Passing			
	Black Creek	Illinois #6	Pittsburgh #8	Pocahontas #3
192	100.0	100.0	100.0	100.0
128	99.9	99.9	100.0	100.0
96	99.7	99.6	100.0	100.0
64	88.7	83.3	92.5	96.8
48	81.4	73.3	84.4	93.4
32	58.4	46.5	62.2	77.4
24	45.6	34.0	47.8	64.7
16	31.8	23.1	33.3	47.6
12	22.3	16.1	23.4	35.4
8	14.7	11.1	16.4	24.3
6	10.5	8.1	11.8	17.5
4	6.9	5.7	8.3	11.5
3	4.7	4.0	5.9	7.9
2	3.0	2.7	4.2	5.2
1.5	1.7	1.5	2.6	3.3
1	1.4	1.2	2.1	2.7
Max σ (psi)	127.32	152.79	190.99	477.47
Max ϵ_v	24017.76	34070.4	20872.8	28491.84
Poisson Ratio	13.48×10^{-3}	18.12×10^{-3}	17.7×10^{-3}	15.27×10^{-3}

Table 76 The stress, strain and Poisson ratio of a compressed cake made from a 50 x 60 mesh size Pocahontas #3 coal (19100 psi)

Stress (psi)	Strain		Poisson Ratio
	Vertical	Horizontal	
15.92	5101.20		
31.83	7441.20	20.24	2.71×10^{-3}
47.75	10455.12	40.48	3.87×10^{-3}
63.66	13478.40	75.90	5.63×10^{-3}
79.58	16211.52	101.20	6.24×10^{-3}
95.49	18401.76	131.56	7.15×10^{-3}
111.41	20124.00	151.80	7.54×10^{-3}
127.32	21930.48	177.10	8.08×10^{-3}
143.24	23446.80	212.52	9.06×10^{-3}
159.15	24935.04	247.94	9.94×10^{-3}
175.07	26479.44	283.36	10.70×10^{-3}
190.99	27883.44	323.84	11.60×10^{-3}
206.90	29427.84	364.32	12.38×10^{-3}
222.82	30878.64	414.92	13.44×10^{-3}
238.73	32348.16	465.52	14.39×10^{-3}
254.65	34004.88	516.12	15.15×10^{-3}
270.56	36279.36	581.90	16.04×10^{-3}

Table 77 The stress, strain and Poisson ratio of a compressed cake made from a 50X60 mesh size Pocahontas #3 coal (25,500 psi)

Stress (psi)	Strain		Poisson Ratio
	Vertical	Horizontal	
15.92	2227.68		
31.83	5073.12	15.18	2.99×10^{-3}
47.75	7890.48	30.36	3.85×10^{-3}
63.66	10258.56	40.48	3.95×10^{-3}
79.58	12392.64	55.66	4.49×10^{-3}
95.49	14526.72	70.84	4.88×10^{-3}
111.41	16267.68	96.14	5.91×10^{-3}
127.32	18167.76	121.44	6.68×10^{-3}
143.24	19674.72	141.68	7.20×10^{-3}
159.15	21350.16	172.04	8.06×10^{-3}
175.07	22782.24	192.28	8.44×10^{-3}
190.99	23961.60	217.58	9.08×10^{-3}
206.90	25328.16	253.00	9.99×10^{-3}
222.82	26676.00	283.36	10.62×10^{-3}
238.73	28154.88	313.72	11.14×10^{-3}
254.65	29437.20	354.20	12.03×10^{-3}
270.56	30990.96	394.68	12.73×10^{-3}
286.48	33190.56	435.16	13.11×10^{-3}

Table 78 The stress, strain and Poisson ratio of a compressed cake made from a 200X270 mesh size Pocahontas #3 coal (25,500 psi)

Stress (psi)	Strain		Poisson Ratio
	Vertical	Horizontal	
15.92	2246.40		
31.83	3341.52		
47.75	4305.60		
63.66	5269.68		
79.58	6233.76	10.12	1.62×10^{-3}
95.49	7048.08	20.24	2.87×10^{-3}
111.41	8105.76	25.30	3.12×10^{-3}
127.32	9565.92	30.36	3.17×10^{-3}
143.24	10717.20	50.60	4.72×10^{-3}
159.15	11334.96	151.80	13.39×10^{-3}

Table 79 The stress, strain and Poisson ratio of a compressed cake made from a 50X60 mesh size Illinois #6 coal (19,100 psi)

Stress (psi)	Strain		Poisson Ratio
	Vertical	Horizontal	
15.92	10642.32	25.30	2.38×10^{-3}
31.83	15912.00	125.60	7.89×10^{-3}
47.75	17952.48	273.24	15.22×10^{-3}
63.66	18195.84	430.10	23.64×10^{-3}
79.58	20526.48	632.50	30.81×10^{-3}

Table 80 The stress, strain and Poisson ratio of a compressed cake made from a 50X60 mesh size Illinois #6 coal (25,500 psi)

Stress (psi)	Strain		Poisson Ratio
	Vertical	Horizontal	
15.92	11353.68	25.30	2.23×10^{-3}
31.83	19843.20	111.32	5.61×10^{-3}
47.75	27246.96	263.12	9.66×10^{-3}
63.66	32179.68	419.98	13.05×10^{-3}
79.58	35259.12	607.20	17.22×10^{-3}
95.49	32469.84	779.24	24.00×10^{-3}

Table 81 The stress, strain and Poisson ratio of a compressed cake made from a 200X270 mesh size Illinois #6 coal (25,500 psi)

Stress (psi)	Strain		Poisson Ratio
	Vertical	Horizontal	
15.92	1778.40		
31.83	3397.68		
47.75	4960.80	15.18	3.06×10^{-3}
63.66	6458.40	25.30	3.92×10^{-3}
79.58	8395.92	30.36	3.62×10^{-3}
95.49	10286.64	45.54	4.43×10^{-3}
111.41	12317.76	60.72	4.93×10^{-3}
127.32	14208.48	75.90	5.34×10^{-3}
143.24	16361.28	101.20	6.19×10^{-3}
159.15	18252.00	126.50	6.93×10^{-3}
175.07	20460.96	161.92	7.91×10^{-3}
190.99	23184.72	212.52	9.17×10^{-3}
206.90	25412.40	273.24	10.75×10^{-3}
222.82	25740.00	779.24	30.27×10^{-3}

the coal in making coal cylinders, the higher the stress needed to break the cylinders.

The particle size distributions resulting from the application of load used to compress the coal samples are given on the basis of the initial particle sizes in Tables 82-84. Compare the results listed in these tables with table 71 and table 75, some conclusions can be made. For the coarser coals (50X60 mesh), the higher the pressure applied in making the coal cylinders, the finer the particle size distributions of the coal cakes. This is also a reasonable result and easy to understand. For the finer coals (200X270 mesh), on the other hand, in spite of applying pressure even as high as two times on the coal samples, the size distributions are almost the same for the same coal. This might be because of the high surface energy of the fine particles.

H. SEM-Image Analysis of Ground Coal

The liberation spectra (i.e., weight percent of particles in class vs. composition class) obtained from the SEM-Image analysis work are shown in Figures 15-26 and the shape factor distributions are shown in Figures 27-30. In terms of liberation, one would normally expect that the amount of free carbonaceous material in the 200X270 mesh size class would increase after grinding since the more brittle mineral matter would tend to break into finer size classes. This is clearly the case for the Illinois and BC coals; however, the opposite is true for the Pocahontas coal, while the Pittsburgh coal yields inconclusive results. Of course, the liberation spectrum for a given size class is also influenced by the larger size classes and the overall liberation spectrum of the feed material. Thus, it is difficult to draw any general conclusions about the shape of the spectrum for a given size class without knowing the entire liberation spectrum of the feed. In general, however, it appears that there is no significant difference in the liberation spectra obtained using either sand or steel media. For three out of four of the coal samples, the liberation spectra for the two media types are almost identical. Only in the case of the Pittsburgh coal, do the data indicate that liberation of carbonaceous material is improved with steel media. Thus, it is probably not fair to draw any conclusion concerning preferential liberation with changes in media type.

In terms of shape, Figures 27-30 clearly show a shift in the shape factor distribution to more circular shapes (i.e. the distribution shifts closer to 1) after grinding, with the shift being more pronounced for the sand media. This shift may be more easily compared by looking at the mass mean shape factors listed in the symbol key for each figure. Thus, it appears that the sand grinding media produces a more spherical product shape.

Table 82 The particle size distributions resulting from the compression of 50 x 60 mesh coal at 19,100 psi and the maximum stress, strain and Poisson ratio exhibited by the respective dry cakes

Size	Cumulative Weight Percent Passing	
(mesh)	Illinois #6	Pocahontas #3
50	100.00	100.00
60	84.76	96.93
100	38.94	67.17
150	27.28	54.31
200	17.49	42.08
270	11.79	18.83
Max σ (psi)	79.58	270.56
Max ϵ_v	20526.48	36279.36
Poisson Ratio	30.81×10^{-3}	16.04×10^{-3}

Table 83 The particle size distributions resulting from the compression of 50X60 mesh coal at 25,500 psi and the maximum stress, strain and Poisson ratio exhibited by the respective dry cakes

Size	Cumulative Weight Percent Passing	
(mesh)	Illinois #6	Pocahontas #3
50	100.00	100.00
60	85.63	98.24
100	39.23	68.98
150	27.20	56.00
200	17.41	43.16
270	12.37	19.31
Max σ (psi)	95.49	286.48
Max ϵ_v	32469.84	33190.56
Poisson Ratio	24.00×10^{-3}	13.11×10^{-3}

Table 84 The particle size distributions resulting from the compression of 200 x 270 mesh coal at 25,500 psi and the maximum stress, strain and Poisson ratio exhibited by the respective dry cakes

Size (μm)	Cumulative Weight Percent Passing	
	Illinois #6	Pocahontas #3
192	100.00	100.00
128	100.00	100.00
96	100.00	100.00
64	85.50	97.80
48	74.40	95.20
32	48.20	81.50
24	34.40	68.90
16	22.80	50.80
12	15.50	37.50
8	10.50	25.30
6	7.40	18.00
4	5.30	11.20
3	3.70	7.40
2	2.50	4.60
1.5	1.30	3.00
1	1.00	2.50
Max σ (psi)	222.82	159.15
Max ϵ_v	25740.00	11334.96
Poisson Ratio	30.27×10^{-3}	13.39×10^{-3}

Figure 15 Liberation spectra (based on carbonaceous material) for Illinois coal sample.

Figure 16 Liberation spectra (based on pyrite) for Illinois coal sample.

Figure 17 Liberation spectra (based on mineral matter) for Illinois coal sample.

Figure 18 Liberation spectra (based on carbonaceous material) for Pittsburgh coal sample.

Figure 19 Liberation spectra (based on pyrite) for Pittsburgh coal sample.

Figure 20 Liberation spectra (based on mineral matter) for Pittsburgh coal sample.

Figure 21 Liberation spectra (based on carbonaceous material) for Pocahontas coal sample.

Figure 22 Liberation spectra (based on pyrite) for Pocahontas coal sample.

Figure 23 Liberation spectra (based on mineral matter) for Pocahontas coal sample.

Figure 24 Liberation spectra (based on carbonaceous material) for BC coal sample.

Figure 25 Liberation spectra (based on pyrite) for BC coal sample.

Figure 26 Liberation spectra (based on mineral matter) for BC coal sample.

Figure 27 Circular shape factor distribution for Illinois coal sample.
(Mass mean shape factor in parentheses.)

Figure 28 Circular shape factor distribution for Pittsburgh coal sample.
(Mass mean shape factor in parentheses.)

Figure 29 Circular shape factor distribution for Pocahontas coal sample.
(Mass mean shape factor in parentheses.)

Figure 30 Circular shape factor distribution for BC coal sample.
(Mass mean shape factor in parentheses.)

I. Flotation Studies

1. Zeta Potential Measurements

Zeta-potential is defined as the potential difference between the bulk solution and a hypothetical plane, close to the interface, at which shearing of the fluid is considered to begin. Measurements of zeta-potential is helpful to the further study the flotation behavior of ground coal products, dispersion and flocculation behavior. Zeta - potential measurements were carried out using Lazer Zee Meter Model 501. The results of the measurements are given in Fig. 31-34. It was interesting to note that for all coals the sand ground coal product acquired smaller potential than the steel media ground coal product at all pH values. The reason for this behavior needs to be studied further.

2. Flotation Tests

Froth flotation utilizes the differences in physio-chemical surface properties of particles of various minerals. Because of chemical, electrical, or physical attraction between the polar portions and surface sites, the collectors adsorb on the particles with their non-polar ends orientated towards the bulk solution, thereby imparting hydrophobicity to the particles. Since flotation is one of the most popular method employed in ultra-fine coal cleaning, flotation tests were carried out to see the influence of sand and steel grinding media on the flotation behavior of the coals. The size distribution of flotation feeds is shown in Figure 35.

Black Creek Coal

This coal was the hardest coal among the four coals in terms of its grindability. Only frother (MIBC) was added to float this coal. Fig. 36-39 give the flotation results of this coal. Ash content of the flotation concentrate and the flotation recovery based on fixed carbon were used as two main criteria to evaluate the experimental results. From the results, we can see that the floatabilities of the Black Creek coal at different PH are different and the variation for the sand ground coal is greater. At lower pH values, say lower than 6, the ash content in the concentrate obtained for steel ground coal is lower compared with those of sand ground coal. When pH values are higher than 6, however, the flotation concentrates are cleaner for the sand ground coal. Obviously, concentrate of sand ground coal is cleaner at natural pH value. This is favorable to sand grinding of coal. With the increase of the MIBC dosage, the recoveries of the coal become higher for both ground products and the recoveries for steel ground products are higher than those of sand ground products. The maximum recoveries for the both products are the same. This means

Fig. 31 Zeta-potential versus PH for Black Creek Coal

Fig. 32 Zeta-potential versus pH for Illinois #6 coal

Fig. 33 Zeta-potential versus pH for Pittsburgh #8 coal

Fig. 34 Zeta-potential versus PH for Pocahontas #3 coal

Fig. 35 Size Distribution of Flotation Feed

Fig. 36 Ash Content of Concentration as Function of PH Values of Black Creek Coal

Fig. 37 Recovery of Coal as Function of PH of Black Creek Coal

Fig. 38 Ash Content of the Concentration as Function of MIBC Dosage of Black Creek Coal

Fig. 39 Recovery of Coal as Function of MIBC Dosage of Black Greek Coal

that the sand ground Black Creek coal consumes a little more MIBC than that of steel ground coal during flotation.

Illinois #6 Coal

This coal was more difficult to float compared with other coals tested. To float the coal, both frother (MIBC) and collector (kerosene) need to be added, as frother and collector, respectively. The flotation results of Illinois #6 coal are shown in Fig. 40 to Fig. 43. For steel ground Illinois #6 coal, the recoveries of flotation change slightly with the change of pH values and the recoveries are higher than 95% at any pH values. For sand ground Illinois #6 coal, however, the recoveries are much lower at high pH values. On the other hand, the ash content of the concentrates for sand ground coal is lower than those of steel ground coal at any given pH value. At lower kerosene dosage, the recoveries for steel ground coal are higher. But when we reach the highest recoveries for both grinding products, the consumption of collector is the same. The dosage of kerosene had little effect on the ash content of the concentrates.

Pittsburgh #8 Coal

Pittsburgh #8 coal was similar to Black Creek coal in the flotation behavior, with MIBC function as both frother and collector, the dosage of MIBC for both coals was almost the same. Fig. 44 to Fig. 47 show the results of flotation tests of the Pittsburgh #8 coal. The difference in flotation phenomena between the two coals was that the ash contents of flotation concentrates for sand ground Pittsburgh #8 coal was lower compared with the those of steel ground Pittsburgh #8 coal, while this was true at higher pH values for Black Creek coal, and sand ground Pittsburgh #8 coal might have had higher flotation recoveries at some pH values, around PH=7, for example. Also, at high pH values, sand ground products had poor floatabilities. Therefore, for this coal, we could get higher flotation recovery with lower ash content in the concentrate using sand as grinding medium at natural PH value.

Pocahontas #3 Coal

This coal exhibited superior floatability. Without adding any flotation reagent, higher than 90% recovery was obtained with ash content of the concentrate lower than 2%. For this coal, the flotation results for sand ground and steel ground products are almost the same. The results are reasonable. Sand ground feed had cleaner flotation concentrate than steel ground feed, with a little lower recovery. Fig. 48 and Fig. 49 show the flotation results for this coal.

Fig. 40 Ash Content of Concentration as Function of PH Values of ILlinois #6 Coal

Fig. 41 Recovery of Coal as Function of PH Values of Illinois #6 Coal

Fig. 42 **Ash Content of the Concentration as**
Function of Kerosene Dosage of Illinois #6 Coal

Fig. 43 Flotation Recovery as Function
of Kerosene Dosage of Illinois #6 Coal

Fig. 44 Ash Content of Concentration of Pittsburgh #8 Coal as Function of PH Values

Fig. 45

Flotation Recovery of Pittsburgh #8 Coal as Function of PH Values

Fig. 46 Ash content of Concentration as Function of MIBC Dosage of Pittsburgh #8 Coal

Fig. 47 **Recovery of Coal as Function**
of MIBC Dosage of Pittsburgh #8 Coal

Fig. 48

Ash Content of Concentration as
Function of PH of Pocahontas #3 Coal

Fig. 49 Flotation Recovery of Coal as Function of PH Value of Pocahontas #3 Coal

From the flotation test results we can convincingly argue that the sand ground coals' flotation concentrates were cleaner i.e. contained less ash than the steel ground coals. This might be partly due to the finer grinding products (see Fig. 35) and / or to the good dispersion properties in the flotation pulp of sand ground coals. We can draw a conclusion that using sand as grinding medium, ground coal had no adverse effects on the flotation results.

IV. SUMMARY

This project was an effort in the direction towards developing an energy efficient and environmentally clean grinding system. Based on the results it is clear that silica sand is a viable alternative for steel shot in fine grinding of coal. In addition to the low costs of silica sand, there are also the benefits of low specific energy consumption and wear associated with the use of silica sand. Other obvious advantages are minimal heat generation which will keep coal less oxidized, low level of sound involved in the grinding will make the process more energy efficient and it is invariably expected that there will be savings in manpower time because sand media do not require media cleaning and inert atmosphere for storage which is usually not the case with steel media. However, the only disadvantage we can see that the unit capacity of a mill may be reduced slightly when silica sand is used as a substitute for steel media.

- 1) Reduced power consumption, i.e. specific energy input (kwh/t) by a factor of 50%
- 2) Improved product quality, i.e. no contamination of ground coal product from media wear such as Fe, Cr, Ni, Mn, etc.
- 3) The average media wear of silica sand was around 0.8kg/ton whereas steel media wear was measured to be around 2.4 kg/ton of coal. Considering the high cost of media (\$10/lb), sand grinding of coal is very economically attractive.
- 4) Liberation of carbonaceous material in the 200X270 mesh size class improved after grinding for the Illinois and the BC coal samples. On the other hand, the amount of liberated carbonaceous material decreased for the Pocahontas sample, while the results for the Pittsburgh sample were inconclusive.
- 5) Particle shape in the 200X270 mesh size class was found to become significantly more spherical after grinding.

- 6) Media type appeared to have no significant effect on the liberation spectra, and, in fact, for three out of four of the coal samples the liberation spectra for steel and sand media were nearly identical.
- 7) Sand media was clearly shown to produce a more spherical product shape than steel media in all cases studied.
- 8) Independent fracture mechanics studies on these coals showed that though Pocahontas coal is soft, it requires the highest level of stress before fracturing possibly because of its clay constituents. These data needs to be analyzed further.
- 9). Zeta potential measurement made on coals ground by these two media showed that in general the sand media lowered the potential.
- 10). Overall and for all the coals studied, a relatively cleaner flotation concentrate was obtained from sand ground coal due to combination of reasons: finer size, more sphericity, lower potential, no adsorption of contaminants from steel media on coal particles, etc.

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