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Techno-Economic Potential of Enhanced Coal Recovery through Middlings Liberation and Re-Processing

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TECHNO-ECONOMIC POTENTIAL OF ENHANCED COAL RECOVERY THROUGH MIDDLINGS LIBERATION AND RE-PROCESSING

THESIS

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Mining Engineering in the College of Engineering at the University of Kentucky

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ABSTRACT OF THESIS

TECHNO-ECONOMIC POTENTIAL OF ENHANCED COAL RECOVERY THROUGH MIDDLINGS LIBERATION AND RE-PROCESSING

The typical preparation plant producing coal for the utility market targets a relative separation density in the plant of around 1.60 whereas plants generating metallurgical coal use relative cut point density values approaching 1.50. In some cases, achieving the specified coal quality requires operating at lower cut point values, which results in a significant loss of valuable coal. In these situations, a middlings stream can be produced using a secondary separator or a three-product unit, which would allow crushing of the middlings for liberation purposes and re-introduction into the plant feed. In this manner, higher quality coal can be produced while maximizing plant yield.

A detailed laboratory analysis was conducted to study the liberation characteristics resulting from the crushing of middlings at different top sizes. The experimental data were later used as input for modeling and simulation of plant flowsheet in LIMN. Simulations were run for several regrinding cases. The results of the current study investigating the economic benefits of middlings liberation and re-treatment are presented and discussed in this thesis. Improvement up to 6% in plant yield with 16-21% reduction in ash and 14-18% sulfur reductions can be achieved by crushing the +1/2 inch middlings to a ½-inch top size.

KEYWORDS: Middlings, cut point, three-product separator, liberation, LIMN, Modeling and simulation.

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April 18th, 2016
Date

TECHNO-ECONOMIC POTENTIAL OF ENHANCED COAL RECOVERY THROUGH MIDDLINGS LIBERATION AND RE-PROCESSING

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DEDICATION

This thesis is dedicated to my mother and father.

I have been extremely fortunate to have been brought up by them, who instilled in me the desire to continue my education. Without their help and support this research would not have been possible.

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I would like to express my deepest gratitude to all those who provided insight and expertise that greatly assisted this research.

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I am thankful to GT Global for having funded the research. I would like to extend my sincere thanks to the Alliance Resource Partner, LP for facilitating us to conduct a test at Dotiki plant. I am also grateful to the Dotiki plant management for having us tour their plant and for all their efforts in ensuring successful samples collection.

I would like to express my sincere gratitude to my fellow graduate students especially Abhijit Bhagavatula without whom conducting the various test programs and laboratory analysis for this project would have been impossible. Further thanks to the whole Mining engineering department for creating a wonderful atmosphere, which made my stay at the department truly memorable.

Finally, I would like to thank my family for all their support and encouragement.

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1 Introduction

1.1 Background

The typical coal preparation plants of United States use relative cut point density values approaching 1.60. However, the Illinois Basin coal plants are often required to operate at lower density cut points below a 1.5 relative density value to provide clean coal with low sulfur content. For a two product separator, a low density separation often results in a substantial loss of valuable coal. Introducing a three-product separator would allow the capture of such middlings which could be further retreated to ensure maximum recovery of valuable coal.

Coal Deposits

The coal-bearing regions of the U.S. are divided into three main areas: Appalachia Basin, Illinois Basin and Powder River Basin. Powder River Basin has the biggest reserves in the U.S. followed by the Illinois Basin. Figure 1.1 shows the major coal basins of the U.S.

This research project was performed using coal from the Dotiki Mining Complex operated by Alliance Resource Partner, LP located in Western Kentucky which extracts coal from the Kentucky No. 13 seam in the Illinois Basin. The Illinois Basin extends over an area of approximately 53,000 sq. miles in East Central United States. It encompasses a large portion of Illinois and extends up to Southwestern Indiana and Western Kentucky. This basin is one of the oldest coal producing regions in the U.S. dating back to early 1800s. The Illinois basin has an estimated reserve of 50 billion tons of recoverable coal, making it the second largest basin in the country only behind the massive Powder River Basin, which has nearly 115 billion tons of coal. The coal found in Illinois Basin is medium and high volatile Bituminous coal reserves of Pennsylvanian age rocks. The coal reserve is characterized by its high sulfur content and has inherent moisture in the range of 7-9%. The occurrence of ash is irregular and unpredictable for large areas of the individual coal seams. The ash content of Illinois coals lies in the range of 6%- 14%. The average ash content of Illinois coals is about 10%, with variations in the order of 2 to 3%. The heat content of Illinois coals ranges from about 11,000 Btu/lb. on moisture, mineral-matter-free basis in the northwestern part of the basin to about 15,000 Btu/lb. in the southeastern part.

The average heat content of coal ranges from 10,000 -12,500 Btu/lb. The high heat content of the coal is often offset by the loss in value due to the high-sulfur content.

High Sulfur Content

As per the EPA's emissions control standard, Illinois Basin coal is classified as a high sulfur coal. Total sulfur content of Illinois coals ranges from as low as 0.5% to more than 8%. Sulfur content of the coal depends on the type of overburden. Most of the coals that have marine shales and carbonates, as overburden tend to have higher sulfur content, greater than 2.5 percent. Whereas, the coals having non marine gray shales as the roof rocks contain less than 2.5 percent sulfur. The presence of marine shales and limestones in the overburden rocks accounts for the high sulfur content of the Illinois Basin coals.

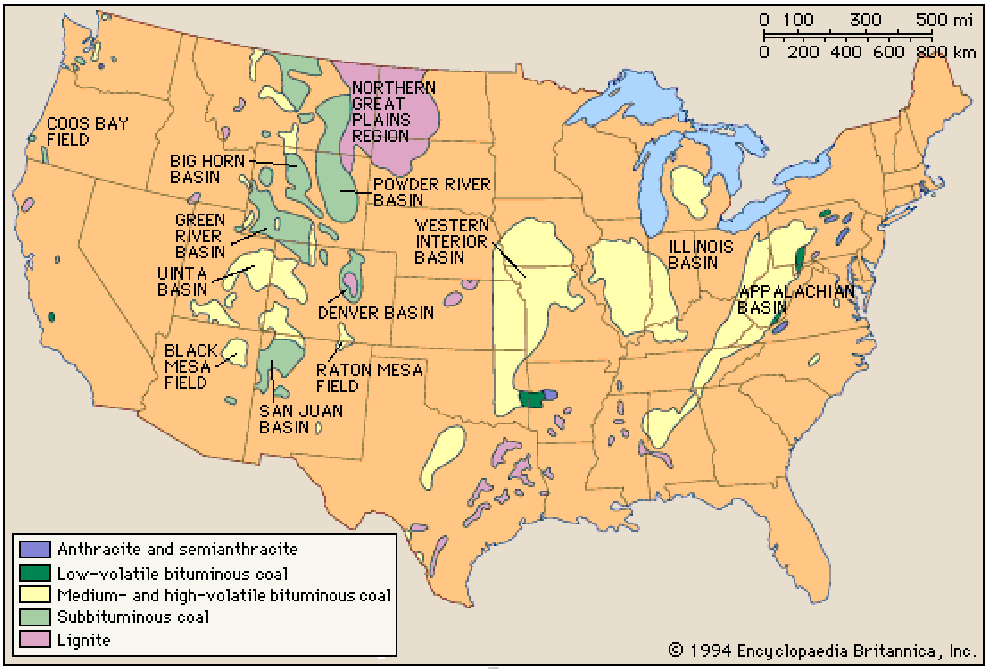

Figure 1-1: Coal Basins of the United States (1994 Encyclopedia Britannia, Inc.)

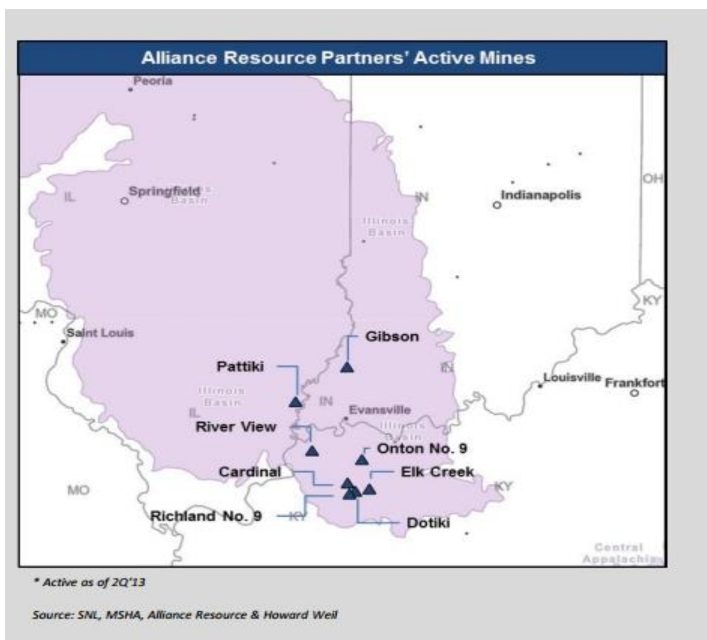

Figure 1-2: Alliance Resource Partners' active mines. (Source: SNL, MSHA, Alliance Resource & Howard Well)

1.2 Problem Statement

As opposed to the regular trends of cutting at 1.6 medium density, the Illinois basin plants have to cut at 1.5 medium density to cut down the high sulfur content of the coal. This low density separation negatively affects their yield and result in significant loss of valuable coal.

With the growing EPA's regulations, it becomes necessary to reduce the sulfur content of the coal. The reduction of high sulfur percentages in coal is a difficult problem. The sulfur content of the Illinois Basin coals is mostly in the form of pyritic and organic sulfur. Organic sulfur is part of the coal structure and uniformly distributed throughout the coal. It is practically not possible to remove the organic sulfur by physical cleaning processes. Whereas, pyritic sulfur occurs as discrete particles within the coal structure and can be removed by physical cleaning if properly liberated. The extent of reduction of pyritic sulfur is a function of particle size reduction. Sometimes the pyritic sulfur may be intricately mixed within the coal matrix. Such coal will require crushing up to fine sizes to liberate the pyritic sulfur. The coal-sulfur distribution in the coal matrix can be so interwoven that the coal is essentially required to be crushed to small sizes for affecting liberation of coal and sulfur particles. It is well known that the fine coal beneficiation processes are generally less efficient than the coarse beneficiation processes. In addition, the handling and transportation of finer products become difficult and expensive. Thus, it is imperative to find an optimum top size for crushing the coal, which would liberate the sulfur and simultaneously maximizes the recovery of clean coal in beneficiation processes.

1.3 Scope of Work

To conduct the study, the Dotiki plant operated by Alliance coal was selected. Alliance coal facilitated to conduct a test at Dotiki plant by setting the medium density at 1.35. Samples around the entire plant were collected. The coarse reject sample was sent to SGS Minerals laboratory to achieve a cut at 1.8 specific gravity medium. Thus, a middlings fraction having specific gravity of 1.35 - 1.8 was obtained. High specific gravity (1.8 sink) coal was the final reject. The middlings fraction was used for further experiment and analysis.

Figure 1-3: Dotiki preparation Plant located in Western Kentucky

The major objective of this research project is to reduce the sulfur and ash content while maximizing the recovery of clean coal produced from the Dotiki preparation plant. This project aims at improve the product quality while positively impacting the plant yield. This research aimed to evaluate the response of middlings fraction to regrinding. To achieve the project goals, the following specific objectives were targeted:

(i) Introduction of a middlings stream using a secondary dense media cyclone or a three-product unit in the Dotiki coal preparation plant.

(ii) Particle size analysis of the middlings produced and evaluation of the washability characteristics of various middling size fractions.

(iii) Cushing of the middlings for liberation purposes at various top sizes using a laboratory scale hammer mill.

(iv) Particle size analysis of the middlings after being crushed to different top sizes and subsequent washability studies.

(v) Designing a new flowsheet with a regrinding circuit.

(vi) Modelling and simulation of the base case and proposed flowsheets using LIMN- an Excel-hosted flowsheet processor.

(vii) Efficiency evaluation of the regrinding circuit and of the overall preparation plant.

(viii) Technical and economic analysis of the proposed design.

1.4 Organization of the Thesis

The thesis is divided into six main chapters. Chapter 1 provides the background leading to the research. It also discusses the purpose of the project. Chapter 2 is focused on the literature review and discusses the previous attempts done in the field of regrinding and sulfur reduction. Chapter 3 discusses the Dotiki preparation plant. Chapter 4 focuses on the experiments done at laboratory of the Department of Mining Engineering, University of Kentucky. Chapter 5 discusses the Modelling and simulation using LIMN. Chapter 6 discusses the technical and economic feasibility of the proposed design. Finally, chapter 7 summarizes the results and conclusions.

2 Literature Review

2.1 Middlings

For a typical coal washability, the intermediate specific gravity fractions have high ash and sulfur content. The low-density fractions comprise the clean coal whereas high-density material is reject. The intermediate density material is called middling. The coal middlings have a relatively high ash content because of associated pyrites and minerals. The middlings consist of large amount of unlocked material. It consists of pyrite rocks blended with coal. Degree of locking of pyrites within coal matrix varies largely within the coal of different regions.

Tables 2.1 and 2.2 show the typical washability data of Illinois No. 6 coal for a coarser (1 x ½ inch) fraction and a finer (6 x 1 mm) size fraction.

Table 2-1 Washability data for 1 x 1/2 inch (coarse) Illinois No. 6 coal used in study

Specific Gravity		**Incremental**		
Sink	**Float**	**Weight%**	**Ash%**	**Sulfur%**
-	1.40	37.08	8.33	3.33
1.40	1.45	2.26	17.20	5.33
1.45	1.50	2.43	20.65	6.15
1.50	1.55	1.28	23.14	6.39
1.55	1.60	1.60	28.69	6.81
1.60	1.65	0.75	32.96	7.31
1.65	1.70	1.11	38.11	7.40
1.70	-	53.49	82.43	5.60

Table 2-2 Washability data for 6 x 1 mm (fine) Illinois No. 6 coal used in study

Specific Gravity		**Incremental**		
Sink	**Float**	**Weight%**	**Ash%**	**Sulfur%**
-	1.40	52.64	8.22	2.87
1.40	1.45	0.60	17.15	3.45
1.45	1.50	2.74	20.82	5.09
1.50	1.55	1.29	24.58	5.68
1.55	1.60	1.55	27.58	6.72
1.60	1.65	0.69	32.39	6.93
1.65	1.70	1.85	38.50	6.46
1.70	-	38.64	82.73	5.88

These two tables indicate that, as the particle size decreases within the same Illinois No. 6 coal, the sulfur values decrease significantly for the intermediate specific gravity fractions, while their incremental ashes remain the same. This is due to the reduction in pyritic sulfur caused by liberation due to finer sizes, even without any crushing. This forms a basis that crushing the middlings to a finer size would result in the liberation of sulfur.

2.2 Middlings Liberation Characteristics

Middlings are relatively high ash materials whose subsequent liberation is possible through size reduction. However, liberation of middlings depends on type of comminution devices and fragmentation mechanisms (Weining Xie, 2013). Middlings particles of size 3 x 0.5 mm from a dense medium cyclone were crushed using by jaw crusher and ball mill to −0.5 mm to generate similar particle size distribution. The particles crushed by jaw crusher showed better mineral liberation than that by the ball mill for each size fraction. For a target ash of 11%, jaw crusher produced 20% higher yields.

The breakage characteristics of middlings and their liberation properties depends on the distribution of mineral matter within the coal. Oliver (1995) crushed middlings from a dense medium separator using a swing hammer crusher. According to the investigation, the original uncrushed middlings did not show any liberation with reducing particle size. However, crushing improved the liberation characteristics of the middlings. It is believed that the change in liberation of the crushed products as a whole is due to the difference in size distributions.

2.3 Previous Attempts at Ash and Sulfur Reduction

Deurbrouck et al. (1966) did a survey of sulfur reduction in Appalachian coals resulting from staged crushing. The investigations indicated that Appalachian coals showed significant sulfur reductions when crushed to a top size of 14 Mesh. A feasible approach for sulfur reductions could be liberation of pyritic sulfur by crushing and subsequent removal by density separation. The study involved crushing of the entire sample to 1 – ½ inch top size before testing. Then the samples were stage crushed through 3/8 inch and 14 Mesh. And in another series of tests, the samples were crushed to 3/8-inch top size only. Crushing of samples to 1 – ½ and 3/8 inch did not indicate any significant sulfur reduction in 1.6 S.G. float. However, the stage crushing of samples to 1- ½ inch, 3/8 inch and 14 Mesh exhibited substantial sulfur reductions in 1.6 S.G. float, especially when crushed down to 14 Mesh top size. Moreover, significant sulfur reductions in the Upper Kittanning coalbed at each successive stage of crushing were observed. On the contrary, the Lower Kittanning coalbed did not show any sulfur liberations by crushing. Another finding of this survey was the constant sulfur content of 1.3 S.G. float regardless of the crushing stage. However, the stage crushing increased the amount of material recovered in 1.3 S.G. float.

Perez (1988) studied the various modes of liberation in the coal-ash-pyrite matrix. The studies showed that the mode of breakage is influenced mainly by the nature of the feed, type of comminution device and their modes of operation. Crushing of raw coal and middlings particles with rotary breaker, jaw crusher, rolls, hammer mill and rod mill indicated different modes of breakage of particles. Breakage of particles in coal occurs primarily by detachment. It is usually desirable to achieve liberation at a coarse particle size. This could be achieved by taking the advantages of inherent zones of weakness between minerals grains and by selecting appropriate comminution device designed to accentuate fracture at the weakness zones.

2.4 Previous Attempts at Middlings Liberation

Several researchers have worked on regrinding and re-treatment of coal middlings to extract maximum valuables out of the coal to increase the recovery.

Perez (1986) developed a simple negative exponential model to describe the liberation of coal and pyrite out of various raw coals and beneficiated fractions using different crushing devices. The study is based on the use of five milling devices: smooth crushing rolls, hammer mill, rod mill, jaw crusher and Mikro – Sampl mill. Liberation studies were conducted on raw coal and middlings. The simple exponential model developed could be used to evaluate the additional coal recovery achieved by recrushing of middlings. The experiments indicated better liberation with finer crusher product discharge.

Claasen (1980) did extensive studies on coking coals of Soutpansberg area in South Africa for maximum recovery routes through middlings treatment. His work indicated that the middlings crushed to 0.8 mm can liberate 2% of run-of-coal at 12% ash. However, crushing the middlings down to 0.21 mm was required to liberate 3.6% of run – of – coal at 12% ash. Thus, a much finer grind was required for substantial liberation purposes. Grinding middlings to finer sizes for liberation purposes generated micro-fines. The micro fines produced could be recovered successfully through froth flotation. The positive response of the micro fines to the froth floatation was however, disparaged by the high moisture retention of micro fines. The loss of fines in the coke-making process from micro fines was another major concern.

Tests programs have been conducted at EPRI Coal Quality Development Center, Pennsylvania to crush the coal to liberate the ash and sulfur. With the increasing environmental regulations, the utility market is willing to pay the premiums for lower sulfur coal (Parkinson, 1985). The studies were done to compare the liberation improvements resulting from crushing of all the raw coal versus middlings crushing. Raw coals and middlings were subjected to five stages of crushing: 6 inch, 1 – ½ inch, 0.6 mm, 0.15 mm and 0.053 mm. Interestingly, at the same energy recovery, the staged middlings crushing approach resulted in 55% SO2 reduction as compared to the conventional cleaning case, which gives 31% SO2 reduction from raw coal. However, crushing of all the raw coal to small sizes such as 0.6 mm for liberation purposes is not economically viable. The utility market cannot support the cost of such fine crushing because of extensive power requirements in crushing. Further, the processes to beneficiate the finer size coals are less efficient and also fine coal transportations are more difficult and expensive. Therefore, crushing only middlings, instead of crushing the entire raw coal presents more judicious solution to liberate sulfur and ash while improving yields.

The Ohio Coal testing and Development Research Facility (OCTAD), 1992, has experimented on capturing of middlings and their subsequent crushing and retreatment. The test aimed to remove sulfur and ash from Ohio coals. Tests were conducted on the Meigs Creek Seam Coal. The studies involved different circuitry arrangement to produce coarse and intermediate size fractions middlings. A total of twelve different flowsheet configurations were investigated to compare the results with conventional coal preparation circuits. All the twelve flowsheets used the similar cleaning circuit for +28 Mesh size fraction. Twelve different circuit configurations for cleaning the fine coal (28M x 0) were discussed. Different combinations of heavy media cyclone and froth flotation were employed. Further, the recirculating medium densities and reagent dosages of flotation were also varied. The circuitry arrangement with fine heavy media cyclone to treat 28M x 150M size fractions showed best performance for SO_2 reductions and recovery improvements. Tests conducted showed significant SO_2 reductions of around 127% with a decrease of 17% in energy recovery as compared to existing commercial plants.

2.5 Problem Being Addressed

The HGI of Illinois basin coal is around 50-60, which is considered as a hard coal. The Illinois No. 6 coal used for this study is not a friable coal which will likely result in minimizing fines production when crushing for liberation purposes.

2.6 Three Product DMC to Capture Middlings

Guohua Technology Corporation (GTC) is a commercial manufacturer of three product DMC. The GTC cyclone is a gravity fed cyclone. It can be successfully applied to treat coal with particle size less than 110 mm.

The GTC three-product cyclone consists of two vessels in series. Figure 2.1 represents a schematic diagram of the GTC three product dense medium cyclone. There is a cylindrical vessel for the primary stage of separation at a relatively low density while, a conical cyclone is used for secondary stage of separation at a higher density There are three discharge openings for clean coal, middlings and refuse, respectively. The use of cylindrical vessel for primary separation facilitates homogeneous and stable media. The use a conical cyclone in secondary stage assists in an increase in the actual separation density which in turn minimizes the misplacement of middlings into refuse.

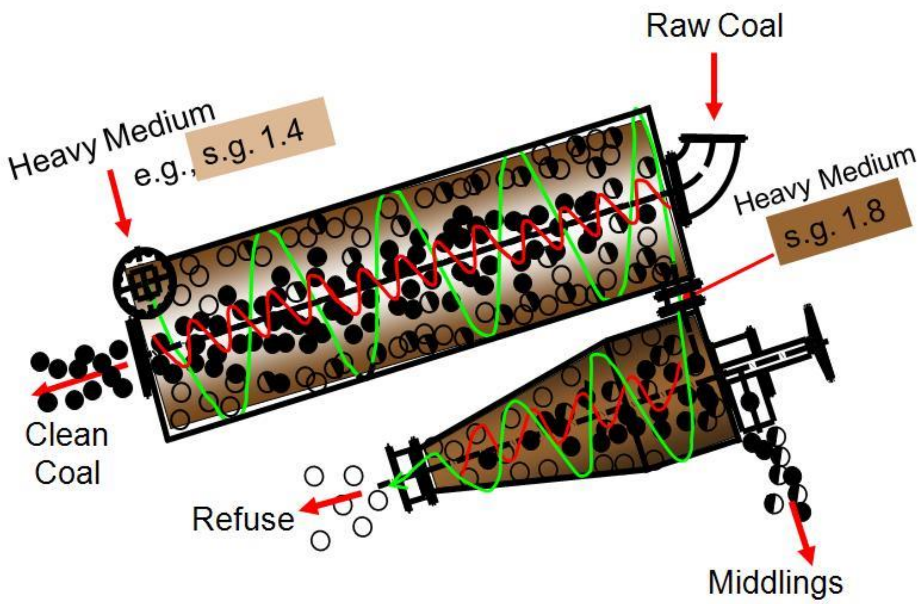

Figure 2-1: GTC Three Product DMC

As opposed to the conventional heavy media cyclones, the raw coal and heavy media are fed separately into the three-product dense medium cyclone. The medium tangentially enters the first stage cyclone under desired head pressure. The raw coal is fed from the top under gravity. The lighter clean coal moves towards the central air core under the influence of centrifugal force and discharged through the bottom of the cylindrical vessel. The heavy media entering the second stage cyclone is already concentrated and thickened due to the action of centrifugal force in the first stage. The secondary cyclone operates at a higher separation density as compared to the primary cyclone to produce middlings and reject.

The GTC three product DMC offers several advantages over conventional dense medium cyclone. As opposed to the conventional approach where coal-media mixture is pumped to the DMC, the gravity feeding approach of the GTC cyclones significantly reduces size degradation, power consumption, and mechanical wearing of the cyclone parts. Moreover, the GTC cyclones are equipped with device for online adjustment of separation density of the secondary stage. This can be achieved by varying the depth of the vortex finder. Another advantage of the GTC cyclones is the cylindrical primary vessel which increases the particle retention time thus, resulting in a cleaner product.

3 Case: Dotiki Processing Plant

Figure 3.1 shows the flow sheet of Dotiki coal preparation plant located in the Western Kentucky.

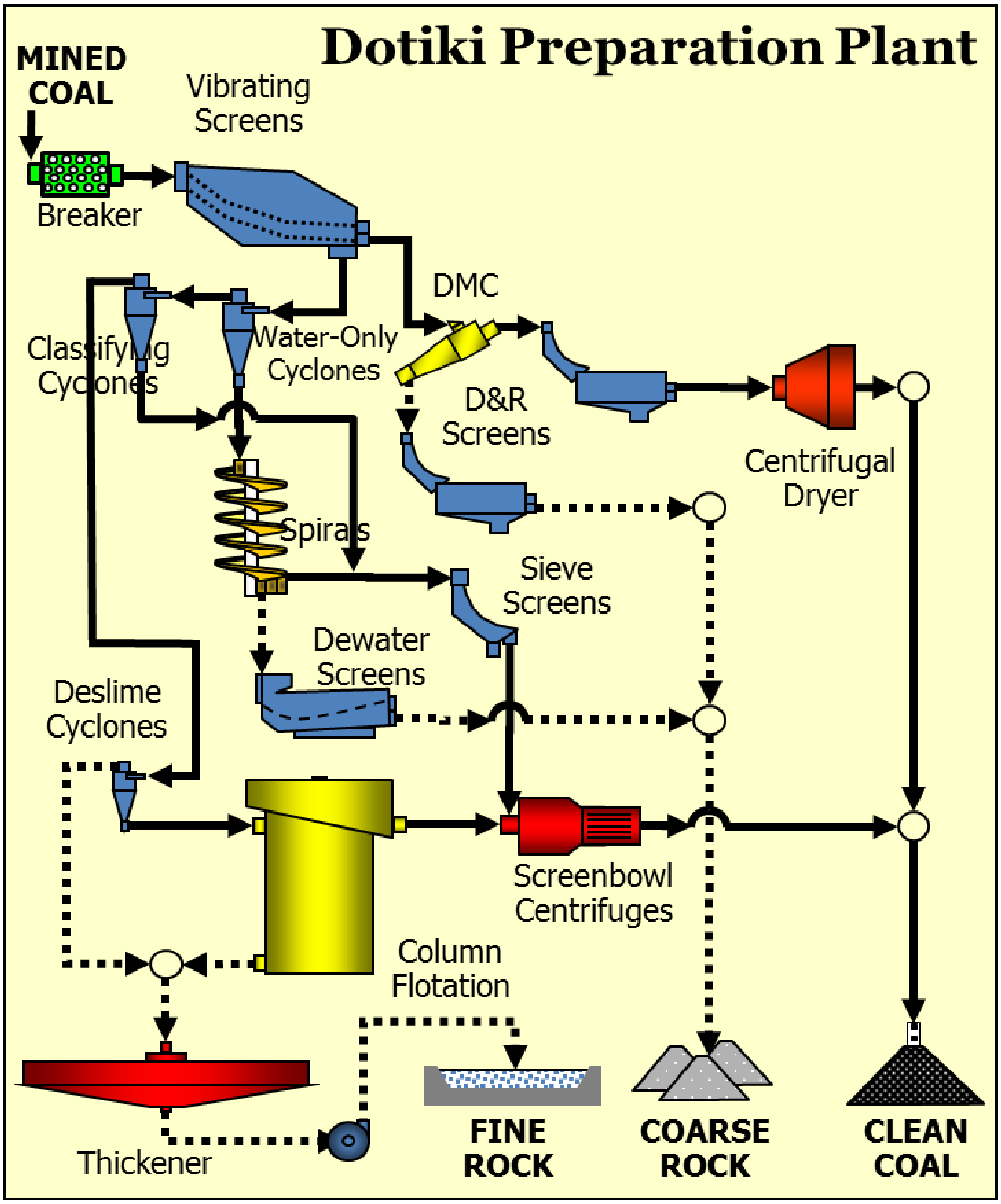

Figure 3-1: The Dotiki preparation plant flowsheet. Source- Dr. Gerald Luttrell

The coal samples were collected from the Dotiki coal preparation plant located in Western Kentucky. Alliance Resource Partner, LP operates the Dotiki Plant. This coal reserve falls in Illinois Basin, which is characterized by high sulfur content. The Dotiki coal preparation plant utilizes a standard 48-inch Krebs dense media cyclone to beneficiate the coarse coal (+ 18 Mesh) and the fine beneficiation (18 x 100 Mesh) uses water only cyclone and spiral circuit. While the ultra-fine coal (-100 Mesh) is treated using froth flotation. The dense media cyclone is a two-product system producing clean coal and rejects. The plant uses a circulating medium density of 1.5. The plant yield ranges between 46 – 50 %. The prep plant is losing significant amount of valuable coal due to low separation densities. The high sulfur content of the coal is another big problem. However, fine generation is not an issue with the Illinois basin coal as it is a hard coal with HGI in the range of 50-60.

The typical monthly average plant performance of the Dotiki preparation plant is shown on table 3.1. As shown in table 3.1, the average plant yield ranges between 46-50%. The typical ash content of the clean coal is 10-11%.

Table 3-1 Typical Monthly Plant Performance

Cut density	**Plant Yield %**	**Ash %**	**Sulfur %**
1.49	46.79	10.19	3.70
1.51	47.57	10.36	3.77
1.52	48.12	10.48	3.81
1.53	49.61	10.52	3.89
1.55	50.27	11.02	3.93

4 Experimental Work

4.1 Experimental Methods and Equipment

The experimental work has been divided into the following three sections:

1. Collection and characterization of middling fraction
2. Crushing of Middlings to different top sizes
3. Float and sink analysis of crushed middlings to study the liberation

4.1.1 Collection of Sample

Alliance plant facilitated to conduct a test at Dotiki Plant by setting the cut density at 1.35 for 3 hours. Samples were collected around the entire plant every 20 minutes for 3 hours. Samples of feed, clean coal, coarse reject, fine reject and thickener underflow were collected. DMC circuit sampling was conducted every 20 minutes over a period of 3 hours. DMC samples were collected by the stop belt method. Feed, clean coal and reject samples were taken simultaneously by the stop belt method. Six barrels of coarse DMC reject was collected. Incremental sampling method was used to collect the samples of thickener underflow.

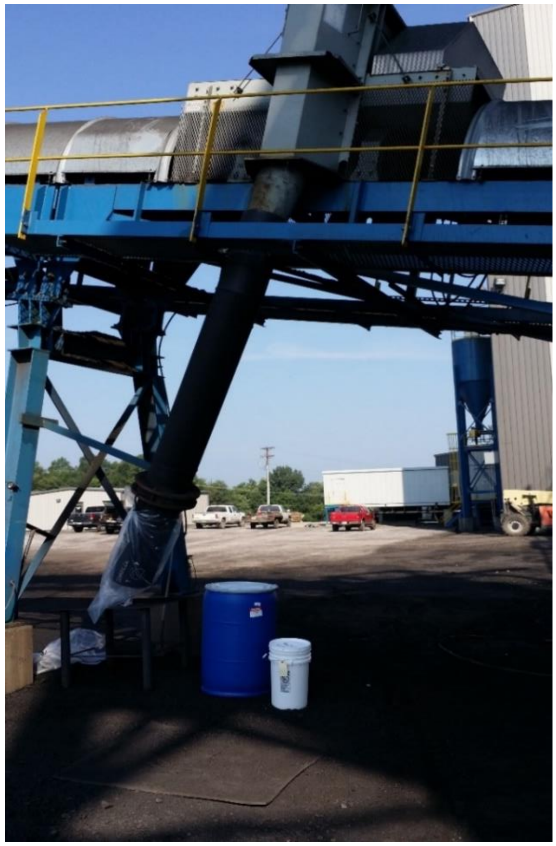

Figure 4-1: Sample collection from clean coal product of Dense Medium Cyclone

The Table 4.1 shows the plant performance on the day of sample collection. The above table indicates that while cutting at a medium density of 1.35, the Dotiki plant produced a yield of 38.44%. The ash content of the clean coal was 8.22% and sulfur content was 3.15%.

Table 4-1 Plant performance on the day of sample collection

	Sulfur %	**Ash %**	**Btu/lb.**
Feed	5.05	52.80	6331
Clean coal	3.15	8.22	13714
Thickener U/F	2.43	67.19	3985

The Dotiki plant currently has a two-product Dense Media cyclone for coarse coal beneficiation. The existing DMC produces clean coal and rejects. The coarse reject coal sample was sent to SGS Minerals laboratory achieve a cut at 1.8. Middlings were generated by preparing a float-sink analysis of the reject material using a medium of 1.8 Specific gravity. A middlings fraction having specific gravity of 1.35 x 1.8 was generated. High specific gravity (1.8 sink) coal was the final reject. The middlings fraction (1.35 x 1.8 SG) was used for further testing and analysis in the laboratory of the Department of Mining Engineering, University of Kentucky.

4.1.2 Sampling of Material

After receiving the middlings coal samples at the laboratory, a representative sample was obtained from the bulk sample using coning and quartering method. The success of any experiment depends on the accuracy of sampling. Sampling is a very important procedure from the very beginning of any experiment. Sampling is a technique used to obtain representative samples that will show the characteristics of the bulk material and it must be done with extreme precautions. The sample size obtained from the plant is often larger than as required for the test procedures in the laboratory. Samples must be reduced in a manner that it reproduces the properties of the original sample. It is often difficult to obtain a representative sample of raw coal at a top size of plus 75 mm. To achieve this, coning and quartering method was used. It involved making conical heaps of the sample on a clean floor, and then flattening it out with the help of shovel. The flattened sample was divided into four zones; the two opposite quarters were discarded, while the other two quarters were combined to form the reduced sample. The same process is repeated until an appropriate sample size is obtained. The final sample left behind is used for further analyses.

4.1.3 Washability Analysis of Uncrushed Middlings

After obtaining the sample of appropriate size, a particle size analysis was done using screens of following apertures: 1 inch, ½ inch and ¼ inch. The screening was done manually with hand screens. This was done to avoid the undesirable breakage of coals which may occur in case of mechanical screening. Following the screening, each size fraction was weighed. The weight of each size fraction was calculated as a percentage of total coal samples. Table 4.2 shows the particle size distribution of middlings before crushing. It is observed that nearly half of the coal falls in 1 x ½ inch size fraction. The + 1-inch fraction in middling is 39% while ½ x 1/4-inch fraction is nearly 13% of the total coal sample. The overall average ash content of each size fraction was around 20%.

Table 4-2 Particle size analysis data of middlings before crushing

Size	Weight%	Ash%	Sulfur%
+1"	39.06	20.16	4.92
-1" + 1/2"	48.08	20.11	5.03
-1/2" + 1/4"	12.86	19.52	5.00

The washability characteristics of coal samples were evaluated by performing float and sink tests. This test determines the distribution of mass in various density fractions. An inorganic liquid LMT was used for preparing media of desired density. LMT liquid is chemically lithium metatungstate. LMT is a heavy liquid of specific gravity 2.95. LMT is preferred because it is economic, safe, affordable and thermally stable liquid. The float and sink analysis was performed using the following specific gravities: 1.3, 1.4, 1.5, 1.6, 1.7, and 1.8. To start with the test, each sample was first placed in 1.3 specific gravity bath. The float was removed with a strainer and washed properly with hot water several times to remove any traces of lithium metatungstate remaining on the surface of coal particles. The cleaned samples were dewatered using filters and dried subsequently. The sink fraction was washed with hot water and then transferred to subsequent higher specific gravity baths. This process was continued until the particles floated and sunk in specific gravity 1.8. The sample was separated into six specific gravity fractions. After the float and sink tests, various float and sink fractions obtained are weighed and assayed for mineral matter content. The float and sink tests were done for all three-size fractions of middlings received after screening: +1 inch, 1 x 1/2 inch and 1/2 x 1/4 inch.

Table 4.3 shows the washability characteristics of +1-inch size coal sample in uncrushed middlings. For +1 inch uncrushed middlings, the analytical data indicates that 81% of total mass has a relative density less than 1.5 and has a cumulative ash content of around 17.89%. The material heavier than 1.7 S.G. is very less.

Table 4-3 Float and sink analysis data of middlings of + 1-inch size fraction

	Incremental floats			**Cumulative floats**		
Float	**Wt.%**	**Ash%**	**Sulfur%**	**Cum Wt.%**	**Cum ash%**	**Cum sulfur%**
1.4	64.98	17.30	4.03	64.98	17.30	4.03
1.5	15.79	20.33	5.62	80.77	17.89	4.34
1.6	11.40	26.36	6.71	92.17	18.94	4.65
1.7	6.22	32.16	8.06	98.39	19.78	4.85
1.8	1.61	43.81	9.21	100.00	20.16	4.92

Table 4.4 shows the washability characteristics of 1 x 1/2-inch size fraction in uncrushed middlings. For 1 x 1/2 inch uncrushed middlings, the analytical data indicates that 75% of total mass has a relative density less than 1.5 and has a cumulative ash content of around 16.67% and 4.32% sulfur.

Table 4-4 Float and sink analysis data of middlings of 1 x 1/2-inch size fraction

	Incremental floats			Cumulative floats		
Float	**Wt.%**	**Ash%**	**Sulfur%**	**Cum Wt.%**	**Cum ash%**	**Cum sulfur%**
1.4	40.71	12.48	3.92	40.71	12.48	3.92
1.5	33.81	21.72	4.80	74.53	16.67	4.32
1.6	15.23	25.80	6.80	89.76	18.22	4.74
1.7	6.93	32.49	8.11	96.69	19.24	4.98
1.8	1.60	43.71	9.06	98.30	19.64	5.05
1.9	1.70	47.17	3.94	100.00	20.11	5.03

Table 4.5 shows the washability characteristics of 1/2 x 1/4-inch size fraction in uncrushed middlings. For 1 x 1/2 inch uncrushed middlings, the analytical data indicates that nearly 69% of the total mass has a relative density less than 1.5 and has a cumulative ash content of around 14.85% and 4.30% sulfur.

Table 4-5 Float and sink analysis data of uncrushed middlings of 1/2 x 1/4-inch size fraction

	Incremental floats			Cumulative floats		
Float	**Wt.%**	**Ash%**	**Sulfur%**	**Cum Wt.%**	**Cum ash%**	**Cum sulfur%**
1.4	50.3	12.67	4.01	50.30	12.67	4.01
1.5	18.57	20.76	5.07	68.87	14.85	4.30
1.6	21.09	25.97	5.69	89.96	17.46	4.62
1.7	7.65	35.69	8.09	97.62	18.89	4.89
1.8	2.38	45.22	9.40	100.00	19.52	5.00

4.2 Comminution using Hammer mill

In this research, a laboratory scale Hammer mill crusher, Model 401XLA1-FC, 230/3/60Hz was used for the crushing the middlings coal which is shown in Figure 4.2. This crusher has a maximum throughput capacity of 4000 pounds per hour while using a 3/8" diameter perforated screen plate; 2500 pounds per hour when using a 3/16" diameter screen. It can be used for crushing 6 inch and smaller size material down to minus 4 mesh sizes. This Hammer mill has a standard rotor speed of 1260 rpm. A 7.5 HP TEFC motor, of specifications 230V, 3 phase, and 60 Hz, powers it. The screen plates determine the top size of the crushed product. Screen plates have round-hole perforations. Screen plates with perforation diameters of 1/8 inch, 1/4 inch, 1/2 inch and 1 inch are used for crushing of middlings.

In hammer mills, comminution occurs by impact rather than compression. Material is fed into the mill's crushing chamber uniformly. Fracture in coal particles occurs by sharp blows applied by the high-speed hammers, which are attached to a shaft. Particles finer than the screen aperture will pass through the screen plate while coarser particles are retained on the screen plate. The oversize particles will be impacted and crushed by the hammers until grounded to the required particle size.

Figure 4-2: Holmes model 401XL Hammer Mill Coal Crusher (courtesy of Preiser Scientific)

After the screen analysis at 1 inch, ½ inch and ¼ inch, the obtained size fractions were weighed and crushed using a hammer mill at different top sizes. Figure 4.3 shows a detailed sampling process done at the laboratory. Four representative samples were obtained from +1-inch coal middlings fraction. The first sample of +1-inch coal was crushed to a top size of 1 inch in hammer mill. The other portion of +1-inch material was crushed to top size ½ inch. The remaining samples were crushed to top sizes 1/4 inch and 1/8 inch. From the 1 x 1/2-inch coal middlings fraction obtained after screening, three representative samples were obtained. The samples were subjected to crushing in a hammer mill at 1/2 inch, 1/4 inch and 1/8-inch top sizes, respectively. From the 1/2 x 1/4-inch coal middlings fraction obtained after screening, two representative samples were obtained. The first sample was crushed to a top size of ¼ inch using hammer mill. The other sample of 1/2 x 1/4-inch coal was crushed to 1/8-inch top size.

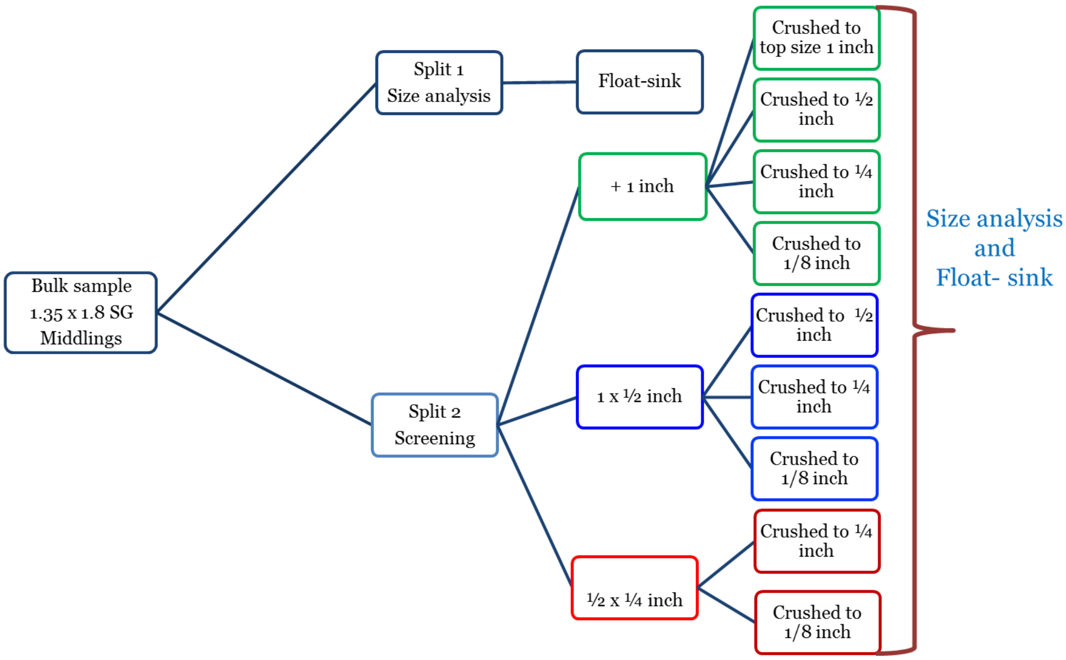

Figure 4-3: Detailed flow chart of middlings crushing

4.3 Liberation from Middlings

4.3.1 Crushing of +1 inch middlings coals to different size fractions

+1 inch middlings coals crushed to top size 1 inch

After crushing the +1-inch coal sample to a top size of 1 inch in a hammer mill, a screen analysis was done using screens of following apertures: 1/2 inch, 3/8 inch, 1/4 inch, 18 mesh and 100 mesh. The size fractions obtained from screening were weighed. The weight of coal in each size fraction was calculated as a percentage of total coal. Table 4.6 shows the particle size distribution of +1 inch middlings fraction after crushing to top size 1 inch. It can be seen that nearly 55% of coal went down to size 1/4"+1 mm after being crushed to 1-inch top size. However, the amount of +1mm coal is 71.8% of total crushed material, which can still be treated using a dense media cyclone in coarse coal beneficiation circuit.

Table 4-6 Particle size analysis data of +1inch middlings particles after crushing to top size 1 inch

Size	Weight%
+1/2"	0.7
-1/2"+3/8"	3.1
-3/8"+1/4"	13.4
-1/4"+1 mm	54.6
-1mm+150um	25.0
-150um	3.2

+1 inch middlings coals crushed to top size 1/2 inch

After crushing the +1-inch coal sample to a top size of 1/2 inch in a hammer mill, a screen analysis was done using screens of following apertures: 3/8 inch, 1/4 inch, 18 mesh and 100 mesh. The size fractions obtained from screening were weighed. The weight of coal in each size fraction was calculated as a percentage of total coal. Table 4.7 shows the particle size distribution of +1 inch middlings fraction after crushing to top size 1/2 inch. Most of the size fraction again went to size 1/4"+1 mm after crushing. The +1mm coal is 65% of total crushed material, which can still be washed using a dense media cyclone in coarse coal beneficiation circuit. However, the -1mm fraction increased by 7% as compared to crushing to 1inch top size.

Table 4-7 Particle size analysis data of +1inch middlings particles after crushing to top size ½ inch

Size	Weight%
-1/2"+3/8"	1.1
-3/8"+1/4"	5.3
-1/4"+1 mm	58.5
-1mm+150um	32.3
-150um	2.7

+1 inch middlings coals crushed to top size 1/4 inch

After crushing the +1-inch coal sample to a top size of 1/4 inch in a hammer mill, screening was done at 18 mesh and 100 mesh. The size fractions obtained from screening were weighed. The particle size distribution of +1 inch middlings fraction after crushing to top size 1/4 inch is presented in Table 4.8. Crushing generated majority of - 1mm + 100 mesh coal fraction, which will be treated in fine beneficiation circuit. However, 38 % of coal is still +1mm, which can be treated using DMC.

Table 4-8 Particle size analysis data of +1inch middlings particles after crushing to top size 1/4 inch

Size	Weight%
-1/4"+1 mm	38.6
-1mm+150um	56.4
-150um	5.0

+1 inch middlings coals crushed to top size 1/8 inch

After crushing the +1-inch coal sample to a top size of 1/8 inch in a hammer mill, screening was done at 18 mesh and 100 mesh. The size fractions obtained from screening were weighed. The particle size distribution of +1 inch middlings fraction after crushing to top size 1/4 is presented in Table 4.9. Crushing to top size 1/8 inch generated a particle size distribution similar to 1/4-inch top size.

Table 4-9 Particle size analysis data of +1inch middlings particles after crushing to top size 1/8 inch

Size	Weight%
-1/8 inch +1 mm	28.7
-1mm+150um	66.0
-150um	5.3

4.3.2 Crushing of 1 x 1/2 inch middlings coals to different size fractions

1 x 1/2 inch middlings coals crushed to top size 1/2 inch

After crushing the 1 x 1/2-inch coal sample to a top size of 1/2 inch in a hammer mill, a screen analysis was done using screens of following apertures: 3/8 inch, 1/4 inch, 18 mesh and 100 mesh. The size fractions obtained from screening were weighed. The weight of coal in each size fraction was calculated as a percentage of total coal. Table 4.10 shows the particle size distribution of 1 x 1/2 inch middlings fraction after crushing to top size 1/2 inch. The particle size distribution followed the same trend as +1inch material crushed to top size 1 inch.

Table 4-10 Particle size analysis data of 1 x 1/2 inch middlings particles after crushing to top size 1/2 inch

Size	Weight%
-1/2"+3/8"	1.0
-3/8"+1/4"	5.6
-1/4"+1 mm	58.3
-1mm+150um	32.5
-150um	2.6

1 x 1/2 inch middlings coals crushed to top size 1/4 inch

After crushing the 1 x 1/2-inch coal sample to a top size of 1/4 inch in a hammer mill, screening was done at 18 mesh and 100 mesh. The size fractions obtained from screening were weighed. The particle size distribution of 1 x 1/2 inch middlings fraction after crushing to top size 1/4 is presented in Table 4.11. 30% of coal is still +1mm, which can be treated using DMC**.**

Table 4-11 Particle size analysis data of 1 x 1/2 inch middlings particles after crushing to top size ¼ inch

Size	Weight%
-1/4 inch +1 mm	38.0
-1mm+150um	56.9
-150um	5.1

1 x 1/2 inch middlings coals crushed to top size 1/8 inch

Table 4.12 shows the particle size distribution of 1 x 1/2 inch middlings fraction after crushing to top size 1/8 inch. The particle size distribution is similar to crushing done at 1/4-inch top size.

Table 4-12 Particle size analysis data of 1 x 1/2 inch middlings particles after crushing to top size 1/8 inch

Size	Weight%
-1/8 inch + 1 mm	30.5
-1 mm + 150 um	64.0
-150 um	5.5

4.3.2 Crushing of 1/2 x 1/4 inch middlings coals to different size fractions

It generated similar PSD trends as 1 x 1/2 inch coals crushed to various top sizes.

The particle size distribution of 1/2 x 1/4 inch middlings fraction after crushing to top size 1/4 inch is presented in Table 4.13.

Table 4-13 Particle size analysis data of 1/2 x 1/4 inch middlings particles after crushing to top size 1 inch

Size	Weight%
-1/4"+1 mm	36.0
-1mm+150um	58.7
-150um	5.3

The particle size distribution of 1/2 x 1/4 inch middlings fraction after crushing to top size 1/8 inch is presented in Table 4.14.

Table 4-14 Particle size analysis data of 1/2 x 1/4 inch middlings particles after crushing to top size 1/8 inch

Size	Weight%
-1/8"+1 mm	29.4
-1mm+150um	64.8
-150um	5.8

4.4 Experimental Results

Liberation studies can be done using float and sink analysis. The washability characteristics of a coal can be provided by float and sink tests using liquids of required specific gravity. The washability tests were conducted to obtain seven density fractions, beginning at 1.3 and increased in increments of 0.1 till specific gravity of 1.9.

4.4.1 Crushing of +1 inch middlings coals to different size fractions

Table 4.15 shows the washability characteristics of +1-inch size coal middlings sample after crushed to a top size of 1 inch in a hammer mill. The analytical data indicates that crushing of middlings have generated 12.4% of 1.3 floats with 6.66% ash and 2.98% sulfur. In the crushed sample, nearly 71% of total mass has a relative density less than 1.5 and has a cumulative ash content of around 12.51% and 3.51% sulfur. The material heavier than 1.9 S.G. is around 7%.

Table 4-15 Float and sink analysis data of + 1 inch middlings crushed to top size 1 inch

	Incremental floats			**Cumulative floats**		
Float	**Wt.%**	**Ash%**	**Sulfur%**	**Cum Wt.%**	**Cum ash%**	**Cum sulfur%**
1.3	12.40	6.66	2.98	12.40	6.66	2.98
1.4	39.18	11.27	3.40	51.59	10.16	3.30
1.5	19.61	18.69	4.07	71.19	12.51	3.51
1.6	11.47	29.36	5.26	82.66	14.85	3.75
1.7	6.03	37.20	6.81	88.69	16.37	3.96
1.8	4.29	47.12	8.72	92.98	17.79	4.18
1.9	7.02	60.55	4.60	100.00	20.79	4.21

Table 4.16 shows the washability characteristics of +1-inch size coal middlings sample after crushed to a top size of ½ inch in a hammer mill. The washability data indicates that crushing of +1 inch middlings to top size ½ inch have generated 12.17% of 1.3 floats with 6.45% ash and 2.96% sulfur. In the crushed sample, nearly 69% of the total mass has a relative density less than 1.5 and has a cumulative ash content of around 12.3% and 3.46% sulfur. The material heavier than 1.9 S.G. is around 9.5%.

Table 4-16 Float and sink analysis data of + 1 inch middlings crushed to top size 1/2 inch

	Incremental floats			**Cumulative floats**		
Float	**Wt.%**	**Ash%**	**Sulfur%**	**Cum Wt.%**	**Cum ash%**	**Cum sulfur%**
1.3	12.17	6.45	2.96	12.17	6.45	2.96
1.4	35.91	10.90	3.26	48.08	9.77	3.18
1.5	20.72	18.15	4.12	68.80	12.30	3.46
1.6	11.17	26.39	5.77	79.97	14.26	3.79
1.7	6.23	34.80	7.17	86.20	15.75	4.03
1.8	4.33	46.49	9.00	90.53	17.22	4.27
1.9	9.47	61.56	4.55	100.00	21.42	4.29

Table 4.17 shows the washability characteristics of +1-inch size coal middlings sample after crushed to a top size of ¼ inch in a hammer mill. The washability data indicates that crushing of +1 inch middlings to top size ¼ inch have generated 12.60% of 1.3 floats with 6.62% ash and 2.99% sulfur. In the crushed sample, nearly 69% of the total mass has a relative density less than 1.5 and has a cumulative ash content of 11.7% and 3.3% sulfur. The material heavier than 1.9 S.G. is around 9.5%.

Table 4-17 Float and sink analysis data of + 1-inch middlings crushed to top size 1/4 inch

	Incremental floats			Cumulative floats		
Float	**Wt.%**	**Ash%**	**Sulfur%**	**Cum Wt.%**	**Cum ash%**	**Cum sulfur%**
1.3	12.60	6.62	2.99	12.60	6.62	2.99
1.4	40.14	10.68	3.12	52.74	9.71	3.09
1.5	16.08	18.22	3.98	68.82	11.70	3.30
1.6	10.88	26.25	5.49	79.70	13.69	3.60
1.7	7.68	34.24	7.19	87.38	15.49	3.91
1.8	5.03	45.96	8.79	92.41	17.15	4.18
1.9	7.59	62.52	4.38	100.00	20.60	4.19

Table 4.18 shows the washability characteristics of +1-inch size coal middlings sample after crushed to a top size of 1/8 inch in a hammer mill. The analytical data indicates that 66% of total mass has a relative density less than 1.5 and has a cumulative ash content of 11.43% and 3.22% sulfur.

Table 4-18 Float and sink analysis data of + 1-inch middlings crushed to top size 1/8 inch

	Incremental floats			Cumulative floats		
Float	**Wt.%**	**Ash%**	**Sulfur%**	**Cum Wt.%**	**Cum ash%**	**Cum sulfur%**
1.3	14.44	6.22	2.88	14.44	6.22	2.88
1.4	34.04	10.38	3.07	48.49	9.14	3.02
1.5	17.68	17.70	3.78	66.17	11.43	3.22
1.6	12.95	25.08	5.12	79.12	13.66	3.53
1.7	8.29	32.97	7.22	87.42	15.50	3.88
1.8	5.19	45.02	8.30	92.61	17.15	4.13
1.9	7.39	61.62	4.78	100.00	20.44	4.18

From these washability tables, it can be seen that by crushing to finer sizes, the amount of material in 1.5 floats decreases. However, the quality of 1.5 floats improves as ash and sulfur values decrease.

The relative cleanability of middlings after being crushed to different top sizes can be assessed by plotting the cumulative float curves against ash and sulfur values for various regrinding sizes. The above washability data have been used for plotting the cumulative float curves.

Figure 4.4 shows the cumulative mass yield –ash curves for +1 inch middlings coals before crushing and after being crushed to top sizes 1 inch, 1/2 inch, 1/4 inch and 1/8 inch. The curves show the changes in coal cleanability characteristics resulting from crushing to various sizes. From these mass yields – ash plots, it is observed that although crushing coal +1-inch coal to different top sizes resulted in decrease of ash percentage. However, the percent reduction in ash remained fairly constant across all the sizes.

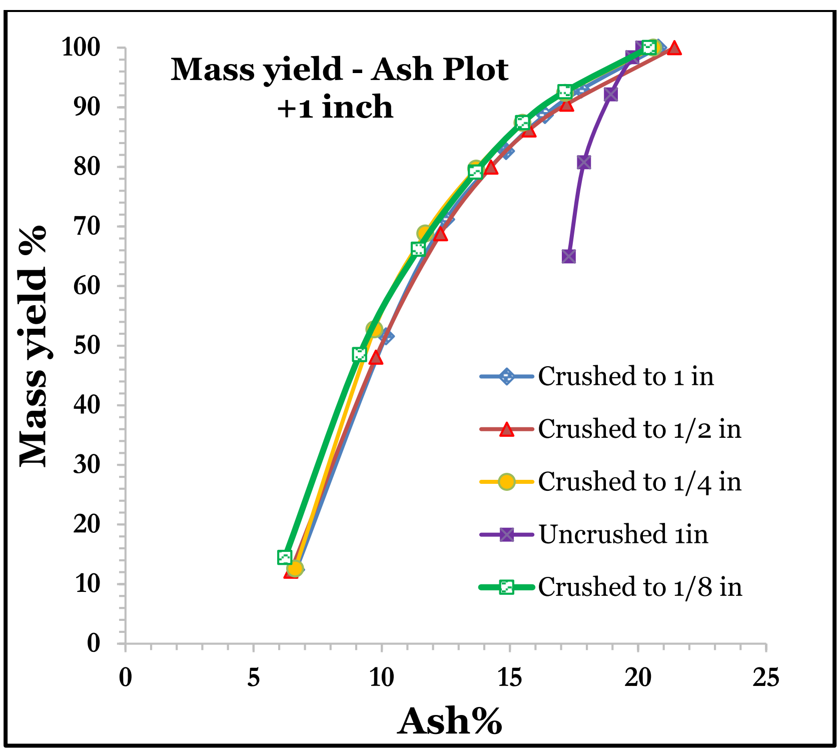

Figure 4-4: Cumulative mass yield – ash curves for various regrinding sizes of +1 inch middlings

Figure 4.5 shows the cumulative float– sulfur curve for +1 inch middlings coals before crushing and after being crushed to top sizes 1 inch, 1/2 inch, 1/4 inch and 1/8 inch. By crushing +1-inch coal to different top sizes, sulfur percentage reduced significantly as compared to the uncrushed middlings. The percent reduction in sulfur increased with finer crushing sizes.

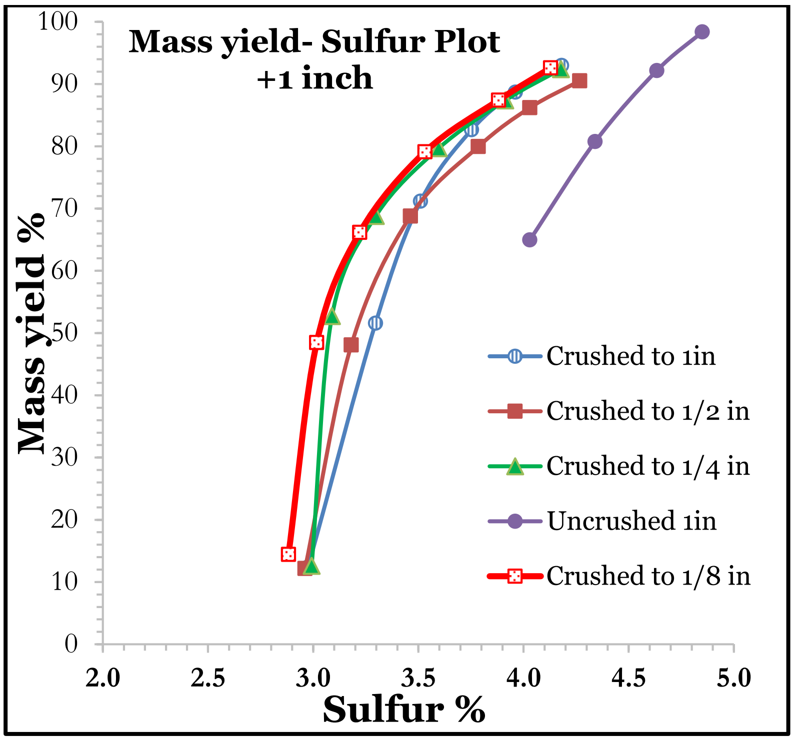

Figure 4-5: Cumulative mass yield - sulfur curves for various regrinding sizes of +1 inch middlings

4.4.2 Crushing of 1 x 1/2 inch middlings coals to different size fractions

Table 4.19 shows the washability characteristics of 1 x ½ -inch size coal middlings sample after crushed to a top size of ½ inch in a hammer mill. It can be seen that crushing has generated nearly 12% of 1.3 floats with flow ash content. The analytical data also indicates that a fairly easy density based separation can be achieved at 1.5 S.G. In the crushed sample, around 66% material is lighter than 1.5 relative density with cumulative ash content of 12.62% and 3.42% sulfur.

Table 4-19 Float and sink analysis data of 1 x 1/2 inch middlings crushed to top size 1/2 inch

	Incremental floats			**Cumulative floats**		
Float	**Wt.%**	**Ash%**	**Sulfur%**	**Cum Wt.%**	**Cum ash%**	**Cum sulfur%**
1.3	11.84	6.43	2.94	11.84	6.43	2.94
1.4	33.52	11.59	3.10	45.37	10.24	3.06
1.5	21.15	17.71	4.20	66.52	12.62	3.42
1.6	15.24	26.35	5.26	81.76	15.18	3.76
1.7	6.37	35.33	7.83	88.14	16.63	4.06
1.8	4.38	45.72	9.05	92.51	18.01	4.29
1.9	7.49	63.00	4.28	100.00	21.38	4.29

Table 4.20 shows the washability characteristics of 1 x ½ -inch size coal middlings sample after crushed to ¼ inch. The washability data indicates that crushing of 1 x ½ inch middlings to top size ¼ inch have generated around 15% of 1.3 floats with 6.15% ash and 2.96% sulfur. In the crushed sample, nearly 68% of the total mass has a relative density less than 1.5 and has a cumulative ash content of around 12.3% and 3.40% sulfur.

Table 4-20 Float and sink analysis data of 1 x 1/2 inch middlings crushed to top size 1/4 inch

	Incremental floats			**Cumulative floats**		
Float	**Wt.%**	**Ash%**	**Sulfur%**	**Cum Wt.%**	**Cum ash%**	**Cum sulfur%**
1.3	14.75	6.15	2.96	14.75	6.15	2.96
1.4	36.67	11.94	3.29	51.41	10.28	3.20
1.5	16.59	18.52	4.05	68.00	12.29	3.40
1.6	11.95	25.08	5.17	79.95	14.20	3.67
1.7	7.72	33.19	6.91	87.67	15.87	3.95
1.8	4.71	46.36	9.00	92.37	17.42	4.21
1.9	7.63	62.84	4.35	100.00	20.89	4.22

Table 4.21 shows the washability characteristics of 1 x ½ -inch size coal middlings sample after crushed to 1/8 inch. It can be observed that crushing down to a top size of 1/8 inch has improved the quality of 1.5 float.

Table 4-21 Float and sink analysis data of 1 x 1/2 inch middlings crushed to top size 1/8 inch

	Incremental floats			Cumulative floats		
Float	**Wt.%**	**Ash%**	**Sulfur%**	**Cum Wt.%**	**Cum ash%**	**Cum sulfur%**
1.3	14.73	5.99	2.90	14.73	5.99	2.90
1.4	37.59	11.55	3.09	52.32	9.98	3.04
1.5	16.29	19.26	4.17	68.61	12.19	3.31
1.6	11.62	24.29	5.70	80.23	13.94	3.65
1.7	7.81	32.06	7.12	88.04	15.55	3.96
1.8	4.99	46.01	8.77	93.03	17.18	4.22
1.9	6.97	62.65	4.10	100.00	20.35	4.21

To evaluate the liberation of middlings after crushing to different sizes, cumulative float curves against ash and sulfur values have been plotted for different regrinding sizes by the use of washability data.

Figure 4.6 shows cumulative float–ash curve for 1 x 1/2 inch middlings coals before crushing and after being crushed to top sizes 1/2 inch, 1/4 inch and 1/8 inch. The curves show the changes in coal cleanability characteristics resulting from crushing to various sizes. From these mass yields – ash plots, it can be seen that although crushing coal 1 x 1/2-inch coal to different top sizes significantly reduced the ash percentage. Maximum percent reduction in ash is observed for the finest crushing size.

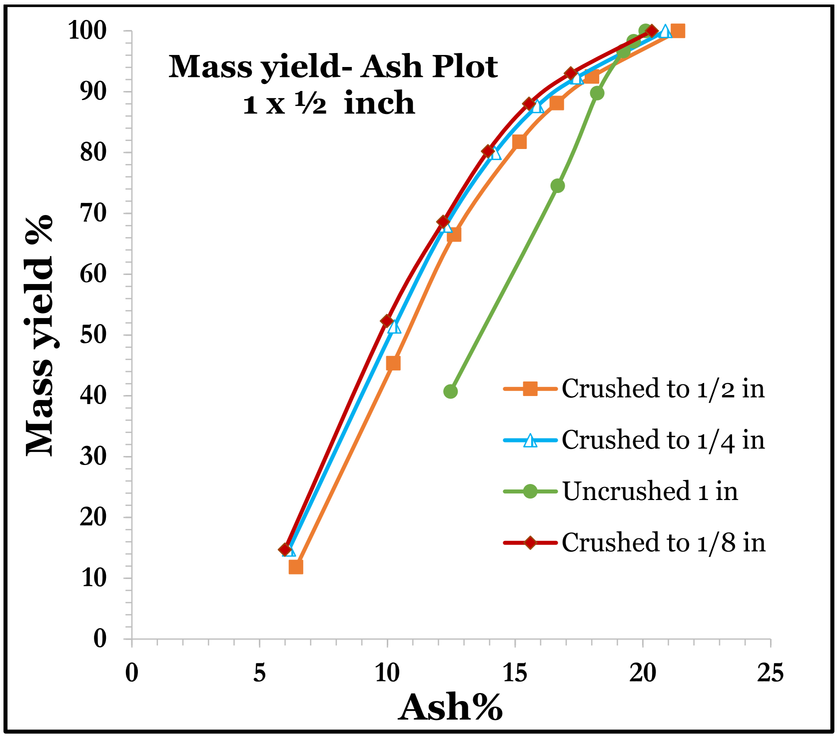

Figure 4-6: Cumulative mass yield – ash curves for various regrinding sizes of 1 x 1/2 inch middlings

Figure 4.7 shows cumulative float- sulfur curve for 1 x 1/2 inch middlings coals before crushing and after being crushed to top sizes 1/2 inch, 1/4 inch and 1/8 inch. By crushing 1 x ½ inch coal to different top sizes, sulfur percentage reduced significantly as compared to the uncrushed middlings. Sulfur liberation increased as we go to finer crushing sizes.

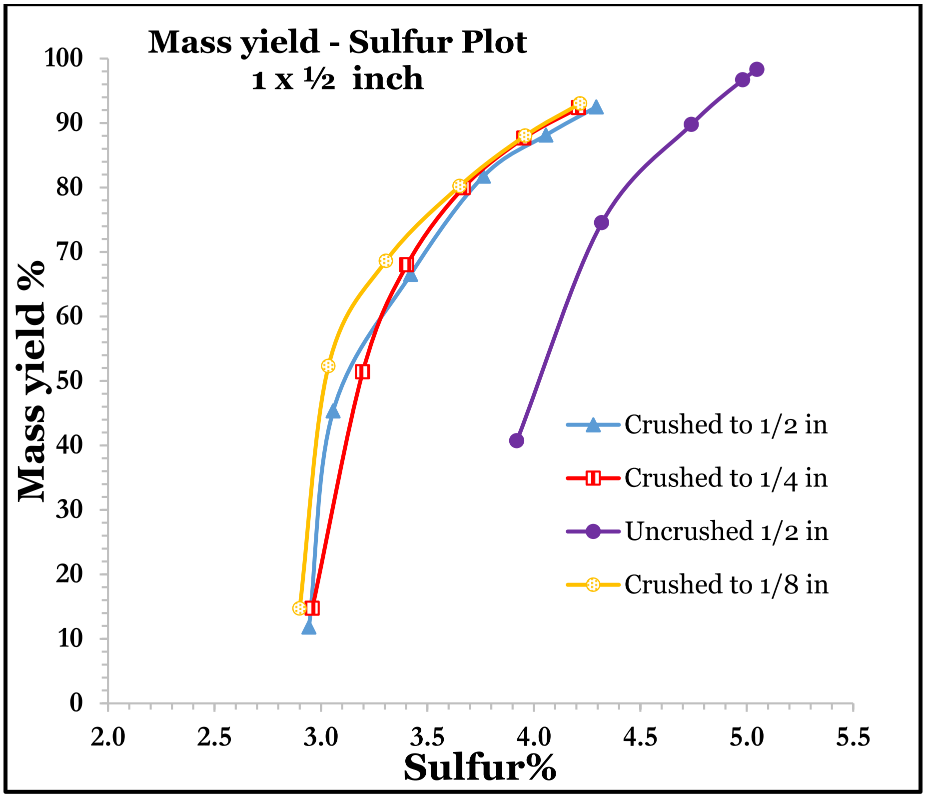

Figure 4-7: Cumulative mass yield – sulfur curves for various regrinding sizes of 1 x 1/2 inch middlings

4.4.3 Crushing of 1/2 x 1/4 inch middlings coals to different size fractions

Table 4.22 and 4.23 show the washability characteristics of ½ x ¼ -inch size coal middlings sample after crushed to ¼ inch and 1/8 inch respectively. The washability data indicates that crushing resulted in materials with 13% of 1.3 floats with low ash and sulfur content in both cases. From the crushed samples, significant amount of material can be recovered at a separation density of 1.5.

Table 4-22 Float and sink analysis data of 1/2 x 1/4 inch middlings crushed to top size 1/4 inch

	Incremental floats			**Cumulative floats**		
Float	**Wt.%**	**Ash%**	**Sulfur%**	**Cum Wt.%**	**Cum ash%**	**Cum sulfur%**
1.3	13.23	6.36	3.04	13.23	6.36	3.04
1.4	39.21	11.89	3.19	52.44	10.49	3.15
1.5	18.09	18.31	4.27	70.53	12.50	3.44
1.6	10.76	25.41	5.61	81.30	14.21	3.72
1.7	7.03	33.62	6.70	88.33	15.75	3.96
1.8	4.45	47.23	8.95	92.77	17.26	4.20
1.9	7.23	61.80	4.74	100.00	20.48	4.24

Table 4-23 Float and sink analysis data of 1/2 x 1/4 inch middlings crushed to top size 1/8 inch

	Incremental floats			Cumulative floats		
Float	**Wt.%**	**Ash%**	**Sulfur%**	**Cum Wt.%**	**Cum ash%**	**Cum sulfur%**
1.3	13.16	6.30	2.90	13.16	6.30	2.90
1.4	37.18	11.57	3.12	50.34	10.19	3.06
1.5	20.60	19.21	3.96	70.94	12.81	3.32
1.6	10.27	24.16	5.43	81.22	14.24	3.59
1.7	6.74	33.18	6.61	87.96	15.70	3.82
1.8	5.01	42.33	8.94	92.97	17.13	4.09
1.9	7.03	62.02	4.87	100.00	20.29	4.15

Cumulative float curves for various grinding sizes have been plotted for a better evaluation of liberation characteristics resulting from crushing the middlings.

The mass yields – ash curves show the improvement in coal washability characteristics resulting from crushing to various sizes. These mass yields – ash plots indicate the decrease in ash content of coal resulting from crushing coal ½ x ¼ -inch coal to different top sizes. However, the percent reduction in ash remained same for the two crushing sizes. Figure 4.8 shows cumulative float–ash curve for ½ x ¼ inch middlings coals before crushing and after being crushed to top sizes 1/4 inch and 1/8 inch.

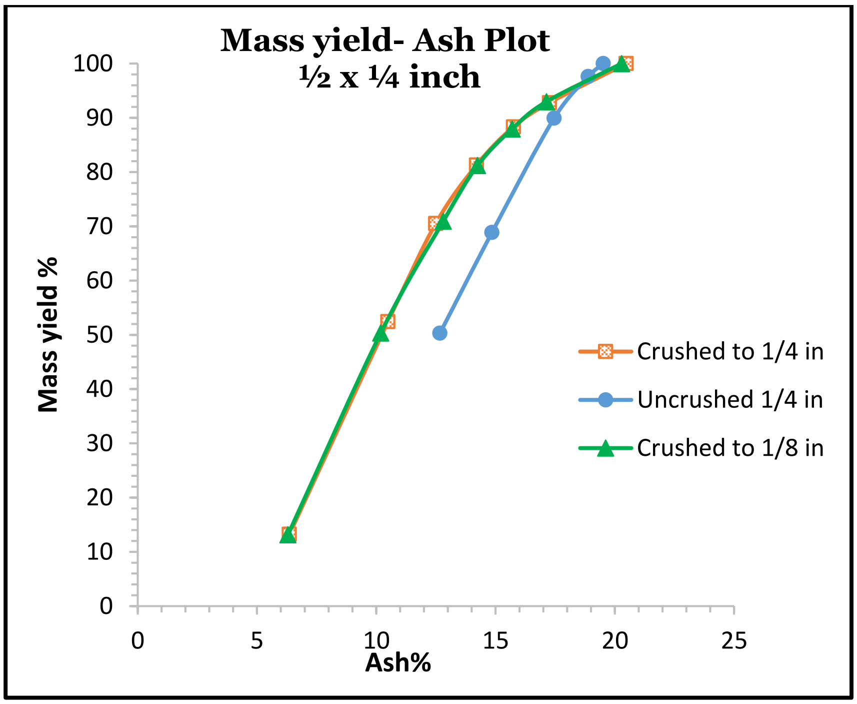

Figure 4-8: Cumulative mass yield – ash curves for various regrinding sizes of 1/2 x 1/4 inch middlings

By crushing ½ x ¼ inch coal to different top sizes, sulfur percentage reduced significantly as compared to the uncrushed middlings. Maximum sulfur reduction can be observed for finest crushing size. Figure 4.9 shows cumulative float–sulfur curve for ½ x ¼ inch middlings coals before crushing and after being crushed to top sizes 1/4 inch and 1/8 inch.

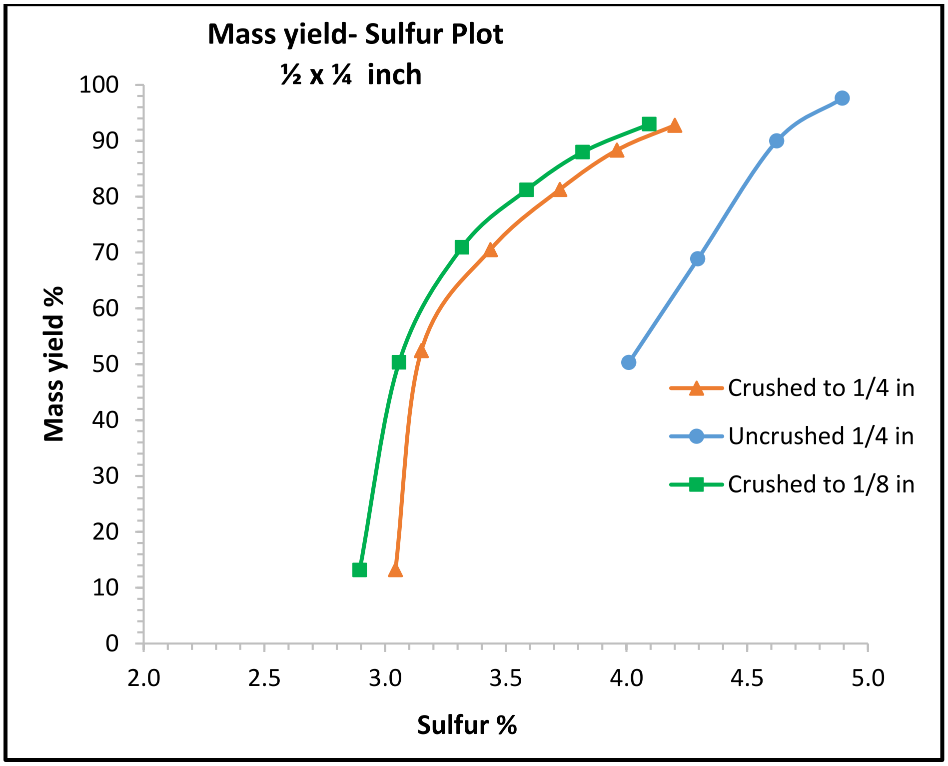

Figure 4-9: Cumulative mass yield – sulfur curves for various regrinding sizes of 1/2 x 1/4 inch middlings

5 LIMN Modeling and Simulation

5.1 Process of LIMN Modeling and Simulation

Limn is an Excel based application that facilitate drawing and modeling of a flowsheet. It allows the user to control and simulate any flowsheet. David Wiseman developed this software in early 1994. To draw the flowsheet, users can select icons for various units from in-built icons. It also allows users to replicate the flowsheet using clone option. Users can even develop their own models or wizards. This makes LIMN more specific to the needs and requirements of the distinct individual.

5.1.1 Using the Coal Wizard

Limn is equipped with several wizards which are basically Microsoft Excel workbooks with an explicit naming and structure. The Wizard Pack Add-On enable users to set up workbook with data structures and models for simulation and analysis of mineral, coal and other mineral processing operations.

The Coal (SG x Size) wizard is used in this research project. The Coal (SG x Size) wizard converts a flowsheet into a model workbook with a two dimensional data structure. It allows to input the assay data and to choose models for simulation from in–built coal–specific models for various units. The particle size distribution and density fractions of the coal should be known. The ash, sulfur and Btu/lb. values by size and by density is required for modeling purpose. For any simulation, the precision of the result depends upon the accuracy and the degree of details of the raw data. For precise results, it is essential to increase the number of size and / or density fractions of the feed washability data. This coal wizard can be used for coal as well as for other minerals also, whose properties can be described in terms of density, particle size distribution and other assays. Comminution-type models are most commonly used in coal wizard. Units such as screens, cyclones, crushers, grinders and thickeners use such models. Universal models, such as mixers and splitters, are also incorporated in coal wizard. Some coal-specific models such as DM separator and generic coal separator models are also available. In addition, users can build their own models too.

5.1.2 Creating the Simulation

The following steps can be followed to create, model and simulate the flowsheet and data sheet in LIMN using Coal Wizard:

1. Draw the process flowsheet using in-built icons for various units.

2. Provide appropriate names to all streams and units within the flowsheet. Later on, the Coal Wizard will use these names while setting up model sheets and data ranges.

3. Choose an appropriate wizard from the wizards' menu. As this research work deals with modeling coal flowsheets, using the Coal (SG x Size) wizard will be apt.

4. Run the Coal Wizard by clicking on the Coal (SG x Size) Wizard button from wizard menu.

5. Analyze the feed washability data to determine the number of size fractions and specific gravity fractions. The Coal Wizard would create the stream data ranges according to these values.

6. Follow the steps on the Coal Wizard dialogs and input all the required information. Modify the number of Size Fractions, SG Fractions and Assays according to the feed washability data. Select appropriate model for each unit from pre-defined models. Users can also build our own models as per their requirements.

The following table shows the basic models used for different units in this project.

Table 5.1 Models selected for various units in the project

UNIT	MODEL
Screens	Double Deck Screen, Single Deck Screen
Dense media cyclone	2 Product Coal DMC
Crusher	1 Product Generic Crusher
Desliming screen	2 Product Desliming Screen
Sumps	1 Product Simple Mixer
Water only cyclone	2 Product DM Separator(Generic)
Spiral	3 Product RD Separator(Generic)
Flotation column	2 Product DM Separator(Generic)
Sieve bend	2 Product Sieve bend (DSM)
Desliming cyclone	2 Product Whiten Cyclone Efficiency
Centrifuge	2 Product Coal Dewatering (Generic)
Screen bowl centrifuge	2 Product Coal Dewatering (Generic)
Thickener	2 Product Simple Dewatering

The coal DMC model is a combination of DSM and JKMRC models. Figure 5.1 shows the 2 product Coal DMC model used for dense media cyclone in this project. The cyclone parameters such as cyclone diameter, inlet diameter multiplier, vortex finder diameter, spigot multiplier, medium density, head pressure, medium ratio, medium solids size and number of cyclones are required as the inputs.

Model for Unit: DMC1

Model Summary				
	Feed	DMC1Floats	DM1sink	Audit Check
Solids t/h	750.0	324.9	425.1	OK
Water t/h	699.6	579.9	119.7	OK
% Solids	51.7	35.9	78.0	-
Magnetite t/h	0.0	0.0	0.0	OK
Ash	44.7	8.7	72.1	-
Sulfur	4.6	3.3	5.6	-

Cyclone Parameters	
Cyclone Diameter (mm)	1200
Inlet Dc Multiplier	0.30
Inlet Diameter (mm)	360
Vortex Finder Dc Multiplier	0.45
Vortex Finder Diameter (mm)	540
Spigot Dvf Multiplier	0.95
Spigot Diameter (mm)	513
Maximum Particle Feed Size	106.4
Medium Density	1.32
Head Pressure (Cyclone diameters)	12.00
Medium ratio	5.00
Medium Solids Size (microns)	30
Average Cutpoint Density	1.459
Cyclone Slurry Split to Spigot	0.266
Density Shift	0.139
Underflow Density	1.574
Overflow Density	1.181
Number of Cyclones Required (Feed)	1.48
No of Cyclones Required (Spigot)	1.326
Calculated Number of Cyclones Required	2
Number of Cyclones Required (Manual Override)	1
Number of Cyclones Used for Calculations	1

Figure 5-1: Model for Coal DMC based on JKMRC and DSM models

For spiral, water only cyclone and flotation column, the DM separator model used which is based on tromp curve model. Required input are the Ep and Rho50 values for each size fraction. To avoid the discrepancies, Ep and Rho50 values for various size fractions are kept constant for modeling the base case and the proposed flow sheet. Figures 5.2 and 5.3 show the DM separator model used for spiral and flotation column based on tromp curve used for the simulations in this project.

Model for Unit: Spirals

Model Summary

	Feed	SPProdu ct	SPMid	SPtail	Audit Check
Solids t/h	214.08	66.136	129.38	18.564	OK
Water t/h	95.714	47.857	23.929	23.929	OK
% Solids	69.104	58.017	84.392	43.688	-
Magnetite t/h	0.00	0.00	0.00	0.00	OK
Ash	65.50	46.377	73.633	76.954	-
Sulfur	6.301	5.20	6.67	7.65	-

Model Parameters

Water Split	To SPProduct	0.50
	(Feed - SPProduct) to SPMid	0.50
Medium Split	To SPProduct	0.50
	(Feed - SPProduct) to SPMid	0.50

Tromp Curve Parameters (split to SPProduct)

Size		Ep	Rho50	Floats - 1.4	1.40 - 1.45	1.45 - 1.50	1.50 - 1.55	1.55 - 1.60	1.60 - 1.65	1.65 - 1.70	1.70 - Sinks
				1.375	1.425	1.475	1.525	1.575	1.625	1.675	1.725
+25	43.30	0.00	0.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
+12	17.32	0.00	0.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
+6	8.49	0.00	0.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
+1	2.45	0.10	1.55	0.873	0.799	0.696	0.569	0.433	0.306	0.203	0.128
+0.15	0.39	0.12	1.55	0.833	0.759	0.666	0.558	0.444	0.336	0.242	0.168
+0.05	0.09	0.13	1.60	0.870	0.815	0.743	0.654	0.553	0.448	0.347	0.259
-0.05	0.04	0.15	1.565	0.801	0.737	0.660	0.573	0.482	0.393	0.309	0.237

Tromp Curve Parameters: Split of (Feed - SPProduct) to SF

Size		Ep	Rho50	Floats - 1.4	1.40 - 1.45	1.45 - 1.50	1.50 - 1.55	1.55 - 1.60	1.60 - 1.65	1.65 - 1.70	1.70 - Sinks
				1.375	1.425	1.475	1.525	1.575	1.625	1.675	1.725
+25	43.30	0.00	0.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
+12	17.32	0.00	0.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
+6	8.49	0.00	0.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
+1	2.45	0.15	1.80	0.957	0.940	0.915	0.882	0.839	0.783	0.715	0.635
+0.15	0.39	0.15	1.90	0.979	0.970	0.957	0.940	0.915	0.882	0.839	0.783
+0.05	0.09	0.15	2.10	0.995	0.993	0.990	0.985	0.979	0.970	0.957	0.940
-0.05	0.04	0.15	2.20	0.998	0.997	0.995	0.993	0.990	0.985	0.979	0.970

Figure 5-2: DM separator model used for spiral

Model for Unit: Flotation column

Model Summary	Feed	FCConc	FCTails	Audit Check
Solids t/h	103.236	21.66	81.577	OK
Water t/h	28.073	14.036	14.036	OK
% Solids	78.621	60.678	85.32	-
Magnetite t/h	0.00	0.00	0.00	OK
Ash	30.117	12.004	34.926	-
Sulfur	4.28	3.178	4.573	-

Model Parameters	
Water Split	
Water Split to FCConc	0.50
Medium Split	
Medium split to FCConc	0.50

Tromp Curve Parameters (to FCConc)

Size		Ep	Rho50	SG Floats - 1.40	1.40 - 1.45	1.45 - 1.50	1.50 - 1.55	1.55 - 1.60	1.60 - 1.65	1.65 - 1.70	1.70 - Sinks
				1.375	1.425	1.475	1.525	1.575	1.625	1.675	1.725
+25	43.30	0.00	0.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
+12	17.32	0.00	0.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
+6	8.49	0.00	0.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
+1	2.45	0.00	0.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
+0.15	0.39	0.10	1.30	0.306	0.203	0.128	0.078	0.047	0.028	0.016	0.009
+0.05	0.09	0.11	1.40	0.563	0.439	0.322	0.224	0.149	0.096	0.061	0.038
-0.05	0.04	0.12	1.45	0.666	0.558	0.444	0.336	0.242	0.168	0.114	0.075

Figure 5-3: DM separator model used for flotation column

7. Lastly, hit the Finish button on the final dialog box, which would create the required data sheets and configuration tables with appropriate ranges.

8. Input the size and density fractions into the appropriate tables of the Configuration sheet.

9. Input the ash, sulfur and Btu/lb. by size and by density data from the feed washability into the relevant table on the Configuration sheet.

10. Input the mass by size by density data for the feed into the relevant table on data sheet.

11. Adjust the model parameters in different spreadsheets for various units.

12. Now the workbook is ready to be solved. Run the Solve from excel toolbar.

Steady state simulations were run for convergence. Most of the steady state simulations converged well within 500 iterations. A converged solution for yield and assays is achieved at the end of every cycle of iterations.

5.2 Base Case of Dotiki Coal Preparation Plant Validation Using LIMN

Figure 5.4 shows the flow sheet of existing Dotiki preparation plant drawn using LIMN.

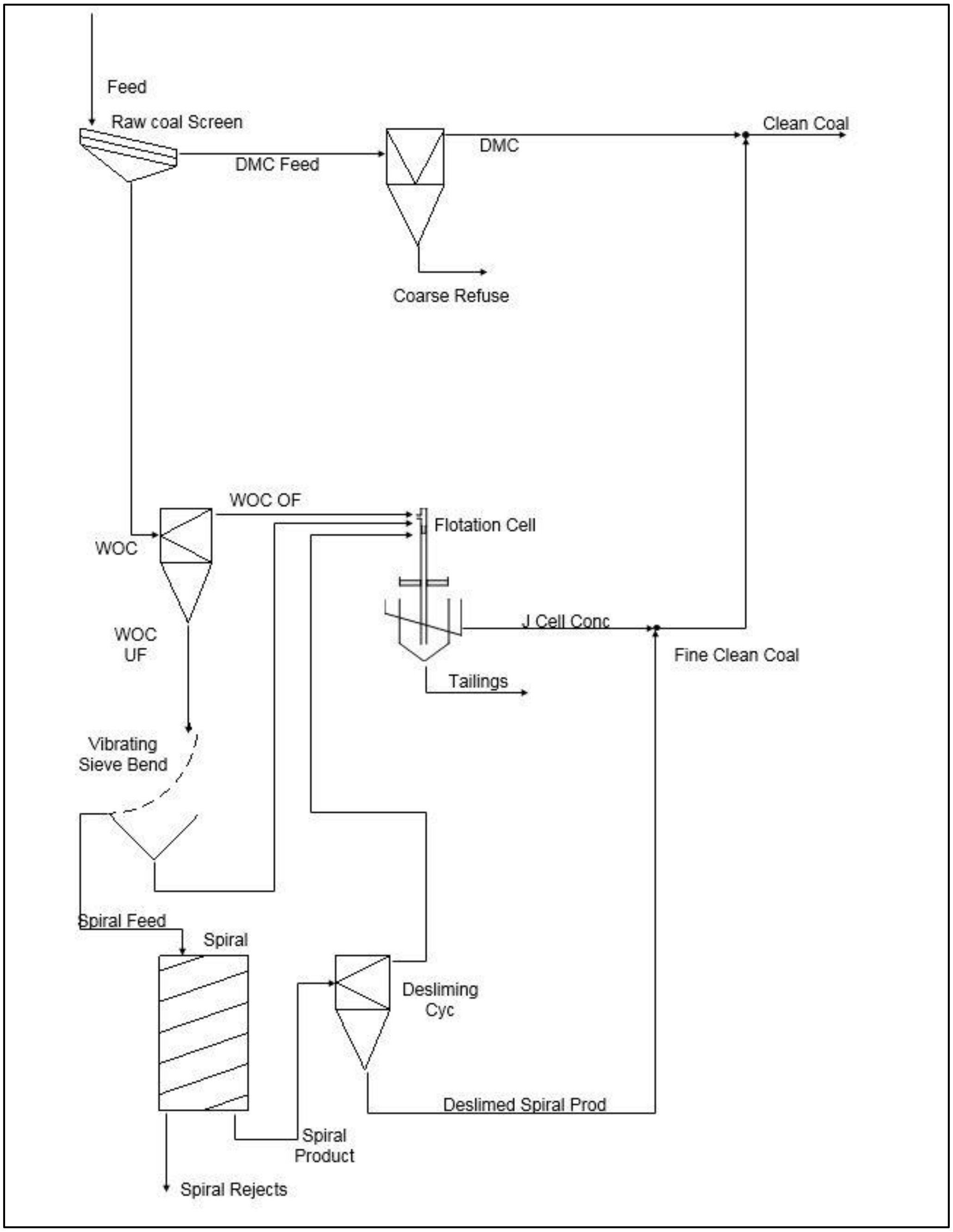

Figure 5-4: Base case flowsheet of Dotiki plant drawn in LIMN

Flowsheet Description

The plant is designed to operate at 900 tons per hour. The raw coal is separated into three size fractions by using a double deck screen: +1/2 inch, -1/2 inch to1mm and -1mm. Different separation circuits are used to treat coarse coal and fine coal. The material coarser than ½ inch and the ½ inch x 1mm fractions are treated by dense medium cyclone. The material finer than 1mm is beneficiated by water only cyclone and spirals. The ultrafine coals are treated using column flotation. The target product ash content is around 8-10%.

The raw coal above 1mm is sent to dense medium cyclone. Plus 1 mm coal falls into a heavy media cyclone tank to mix with dense medium solution. Then, coal and dense medium are pumped together into a dense medium cyclone. Clean coal and tailings are sent to clean coal drain and rinse screen and tailing drain and rinse screen respectively for dense medium drainage. Clean coal is sent to coarse clean coal belt after passing through a centrifuge to further reduce the moisture. Tailing is sent to the refuse belt directly. Effluent from clean coal centrifuge is sent to dilute medium sump.

Particles below 1 mm fall into a fine raw coal sump. -1 mm sample is mixed with clean water and then pumped into water only cyclone for beneficiation. Particle below 0.15 mm is sent to an effluent sump for flotation. 0.15-1mm particle passes through two stage triple start spirals to be separated into three products. Middling from spirals returns to the raw coal sumps for recycling. Tailings are sent to high frequency screen for dewatering. High frequency screen overflow goes to refuse belt and under flow goes to effluent sump. Clean coal from spirals goes to clean coal classifying cyclone sump. The overflow of classifying cyclone consisting of particles below 0.05 mm is sent to fine cyclone feed sump. The underflow of the classifying cyclone goes to the screen bowl centrifuge for further dewatering before being sent to clean coal conveyor belt. Slurry in fine cyclone feed sump is pumped into a desliming cyclone. The overflow of the desliming cyclone goes to thickener and the underflow goes to flotation column. Flotation clean coal goes to screen bowl centrifuge for dewatering and then sent to clean coal belt. Flotation tailing is sent to the thickener.

Base case was validated using Limn. LIMN simulations were run to replicate the original plant conditions.

Table 5-1 Plant performance as obtained from LIMN simulation

Cut density	Yield%	Ash%	Sulfur%
1.35	38.68	8.32	3.21
1.40	39.67	8.87	3.29
1.44	45.33	9.61	3.41
1.48	46.44	10.30	3.57
1.52	47.71	10.54	3.71
1.55	49.86	11.04	3.77

Table 5-2 Typical monthly average plant performance

Cut density	Yield%	Ash%	Sulfur%
1.35	38.44	8.22	3.15
1.49	46.79	10.19	3.70
1.51	47.57	10.36	3.77
1.52	48.12	10.48	3.81
1.53	49.61	10.52	3.89
1.55	50.27	11.02	3.93

Table 5.1 shows the performance of Dotiki Plant while cutting at different medium densities as obtained from LIMN simulation. While, Table 5.2 shows the actual monthly average performance of the Dotiki preparation plant. The results obtained from the Limn simulations were coherent with the actual plant performance. Especially, the yield and ash values showed excellent agreement. However, sulfur values were off by two points. A possible reason for this difference could be software error.

5.3 Proposed Flowsheet of Dotiki Coal Preparation Plant

Figure 5.5 shows the proposed flow sheet of Dotiki preparation plant with a three – product DMC and an additional DMC drawn using LIMN.

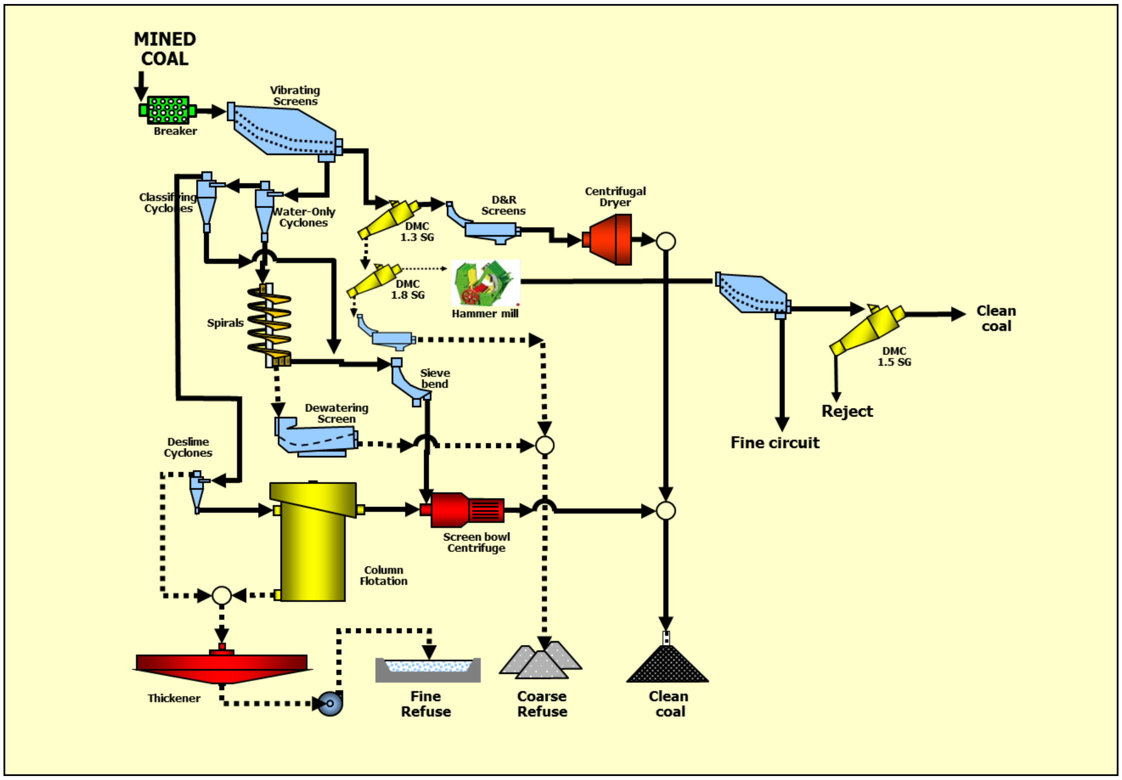

Figure 5-5: Proposed flowsheet of Dotiki plant drawn in LIMN

Flowsheet Description

The plant is designed to operate at 900 tons per hour. The raw coal is separated into three size fractions by using a double deck screen: +1/2 inch, -1/2 inch to1mm and -1mm. Two different separation circuits are used to treat coarse coal and fine coal. The material coarser than ½ inch and the ½ inch x 1mm fractions are treated by dense medium cyclone. The material finer than 1mm is beneficiated by water only cyclone and spirals. The ultrafine coals are treated using column flotation.

The raw coal above 1mm is sent to primary dense medium cyclone operating at 1.3 cut point. Plus 1 mm coal falls into a heavy media cyclone tank to mix with dense medium solution. Then, coal and dense medium are pumped together into a dense medium cyclone.

Clean coal is passed through drain and rinse screen to separate dense medium and coal particles. Clean coal is sent to coarse clean coal belt after passing through a centrifuge to further reduce the moisture. DMC underflow is sent to a secondary DMC cutting at a medium density of 1.8. The float of secondary DMC is passed through a screen. Depending on the regrinding size, different screen apertures of 1 inch, ½ inch and ¼ inch can be used. The screen oversize is crushed in a hammer mill. The crushed product is then screened at 1 mm. The +1 mm coal is treated in an additional DMC cutting at a medium density of 1.5. The 1.5 float is mixed with the coarse clean product and the underflow of DMC is rejected. The -1 mm coal is sent to the fine beneficiation circuit.

Particles below 1 mm fall into a raw coal sump from the raw coal screen. -1 mm sample is mixed with clean water and then pumped into water only cyclone for beneficiation. Particle below 0.15 mm is sent to an effluent sump for flotation. 0.15-1mm particle passes through two stage triple start spirals to be separated into three products. Middling from spirals returns to the raw coal sumps for recycling. Tailings are sent to high frequency screen for dewatering. High frequency screen overflow goes to refuse belt and under flow goes to effluent sump. Clean coal from spirals goes to clean coal classifying cyclone sump. The overflow of classifying cyclone consisting of particles below 0.05 mm is sent to fine cyclone feed sump. The underflow of the classifying cyclone goes to the screen bowl centrifuge for further dewatering before being sent to clean coal conveyor belt. Slurry in fine cyclone feed sump is pumped into a desliming cyclone. The overflow of the desliming cyclone goes to thickener and the underflow goes to flotation column. Flotation clean coal goes to screen bowl centrifuge for dewatering and then sent to clean coal belt. Flotation tailing is sent to the thickener.

5.4 Regrinding Cases for Simulation

Simulations were run for several regrinding cases. For the purpose of comparison, three regrinding cases are selected. Data on these three cases will be presented and discussed in this thesis. The three regrinding cases are:

(i) +1 inch middlings screened out and crushed to a top size of 1 inch

(ii) +1/2 inch middlings screened out and crushed to a top size of ½ inch

(iii)+1/4 inch middlings screened out and crushed to a top size of ¼ inch

5.4.1 Regrinding Circuit Efficiency

Effect of Regrinding Size on Mass Yield of Product

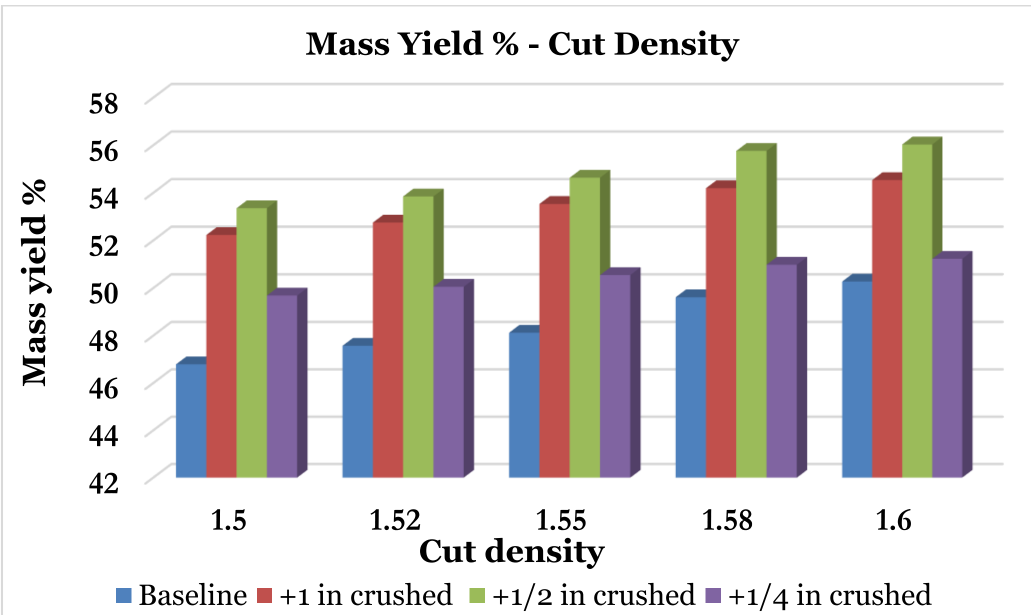

Figure 5-6: Plant yield – cut densities plots for various regrinding sizes

The above Figure 5.6 shows the effect of various regrinding sizes on mass yield of product. This plot indicates that the plant yield improved significantly for all regrinding cases as compared to the base case. However, the regrinding case where all + ½ inch coal was screened out and crushed to a top size of ½ inch showed maximum increase in yield for different cut densities. For instance, when the additional DMC is operating even at higher medium density of 1.6, 56% yield can be achieved.

Effect of Regrinding Size on Clean Coal Ash

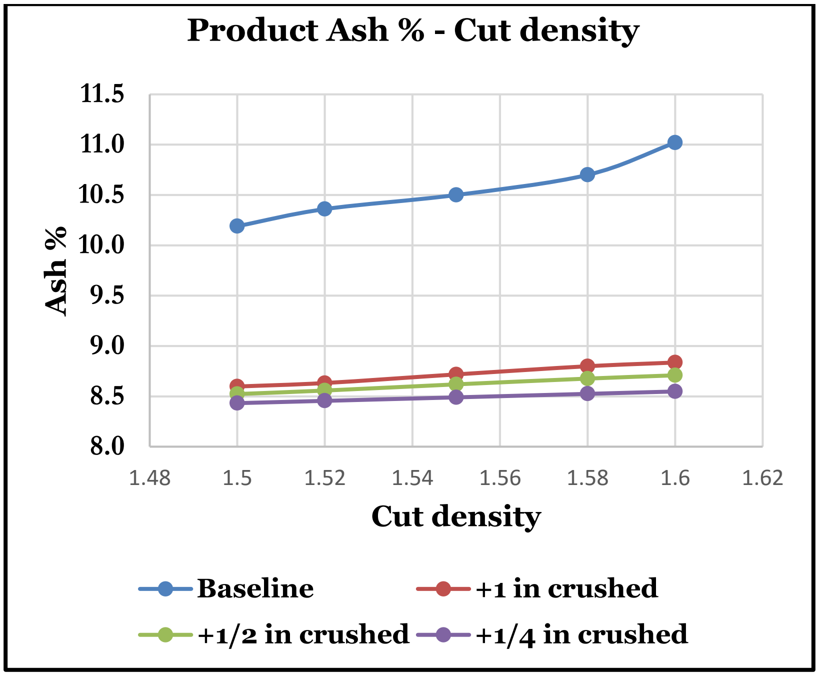

Figure 5-7: Product ash – cut densities plots for various regrinding sizes

Figure 5.7 shows the effect of various regrinding sizes on the ash content of the clean coal. It can be seen that in all the regrinding cases, ash content reduced as compared to the base case. In most of the cases ash values as low as 8.5- 8.7% can be achieved. However, the product quality improved with the finer regrinding sizes.

Effect of Regrinding Size on Clean Coal Sulfur Content

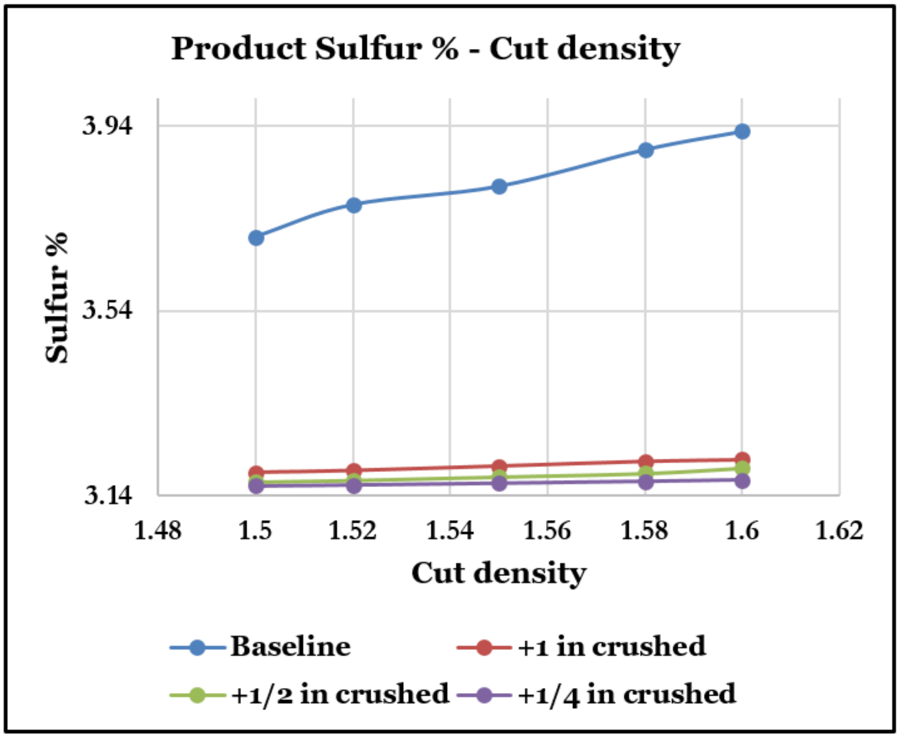

Figure 5-8: Product sulfur - cut densities plot for various regrinding sizes

Figure 5.8 shows the effect of various regrinding sizes on the sulfur content of the clean coal. It can be seen that grinding the middlings to various sizes resulted in substantial reduction of sulfur values as compared to the base case. The case where all +1/4 inch middlings are crushed to a top size of ¼ inch showed best sulfur improvements. While operating at a cut density of 1.5, sulfur values of 3.15% can be achieved.

6 Technical and Economic Analysis

Table 6-1 Comparison of performance of base case and proposed flowsheet of Dotiki Plant

Cut Density	Base Case			Proposed flowsheet			Improvement		
	Plant Yield (%)	Product Ash (%)	Product Sulfur (%)	Plant Yield (%)	Product Ash (%)	Product Sulfur (%)	Yield (%)	Reduction Ash (%)	Reduction Sulfur (%)
1.50	46.79	10.19	3.7	53.35	8.52	3.17	6.56	16.38	14.32
1.52	47.57	10.36	3.77	53.85	8.56	3.17	6.28	17.37	15.92
1.55	48.12	10.48	3.81	54.64	8.62	3.18	6.52	17.75	16.54
1.58	49.61	10.52	3.89	55.76	8.68	3.19	6.15	17.50	17.95
1.59	50.27	11.02	3.93	56.03	8.71	3.21	5.76	20.96	18.32

Table 6.1 shows the comparison of performance of the base case and the proposed flowsheet for the regrinding case where all +1/2 inch middlings are crushed to a top size ½ inch. Simulations were run for different cut densities of additional DMC. The cut densities of additional DMC in the proposed flowsheet were matched with the actual plant's circulating medium densities. The regrinding case where all + ½ inch middlings are crushed to top size ½ inch showed excellent improvements in yield and significant reductions in ash and sulfur values. The striking outcomes achieved from this regrinding scenario are:

(i) Improvement up to 6% in plant yield.

(ii) Reduction up to 16-21% in ash content bringing clean coal ash to around 8.71%.

(iii) Reduction up to 14-18% in sulfur values bringing clean coal sulfur to around 3.21%.

Encouraged by the increase of 6% in yield, an economic analysis was done. Table 6.2 shows the operational parameters and prevailing market rates that are considered for the economic evaluation of yield gain.

Table 6-2 Operational and economic parameters considered for calculations

Parameters	**Values**
Plant throughput	900 tph
Plant operating hours	6000 hours
Selling price of coal per ton	$35
Additional operating cost(for additional units added in new flowsheet) per ton	$3
Increase in yield point	6%

Annual production increase = (.06) *(900tph) *(6000hours/year) = 324,000 tons/year

Annual profit = (324,000 tons/year) *((35-3) $/ton) = $ 10.4 million

Considering the plant operating at 900 tph and 75% availability, the proposed flowsheet is expected to add 270,000 tons of clean coal per year, which would have a value of $ 10.4 million in present market scenario.

7 Conclusions

The primary objective of this research was to investigate the potential of recovery of clean coal from middlings after regrinding and re processing the ground products**.** The project's success would allow the applicability of 3 product DMC to capture the middlings which could be further processed. This research work intended to improve the product quality while positively impacting the plant yield.

The study involved the evaluations using both laboratory analysis and simulations using LIMN to evaluate the regrinding efficiencies. The study involved the investigation of coal samples from the Dotiki plant located in Western Kentucky. The laboratory tests were conducted for various crushing sizes of middlings. Tests were conducted to evaluate the potential liberation to be achieved with changing the crushing sizes. A follow-up study was done using LIMN which is an excel based software for modeling and simulations. The washability data obtained from laboratory experiments were used as input for simulations in LIMN. The base case flowsheet of Dotiki plant was validated using LIMN to match the original plant performance. Using LIMN, a new circuitry arrangement with three product DMC and an additional DMC to treat reground middlings was modeled and simulated to determine any potential improvements in mass yield and quality of target product. Different regrinding cases were run to optimize the mass yield and recovery of product. The goal of project was to determine the optimum conditions which would maximize the plant yield with improvements in target product quality.

A detailed study was carried out on the regrinding and retreatment of middlings which showed promising results. The thesis discusses the potential of introducing a three product dense medium cyclone to capture middlings and their further retreatment. The key outcomes of the research are listed below:

1. The size to which the coal is ground is an important variable determining the liberation of middlings fraction.
2. It is usually desirable to achieve the liberation at as coarse particle size as possible because treatment of fines is less efficient and much expensive operation.

3. Breakage of the particles to liberate the middlings to a size which can be treated in a coarse circuit which is economically beneficial.
4. When treating Illinois Basin coal, fine generation is not an issue with our research work as Illinois coal is considerably hard coal with an HGI of 50 – 60.
5. Balance exists between liberation gains with reduced particle size and the increased amounts reporting to the fine coal circuit with lower efficiency separators.
6. Moisture gains occur due reduced particle size when we go to finer crushing sizes.
7. Crushing the coal in this study increased the -100 mesh fraction percent from 3.0% at a 1-inch top size to 5.5% at a 1/8-inch top size.
8. The production of a middlings stream would subsequently lead to an additional crushing of coarser fractions to improve mass yield and recovery of clean coal stream.
9. A significant amount of ash – forming material (1.8 sink) can be rejected by using a 3 product DMC. The middlings (1.35 x 1.8 S.G. coal) will be treated again at 1.5 cut density in an additional DMC.
10. The results of the simulations of the proposed flowsheet with regrinding and additional beneficiation indicated higher efficiencies than the base case flowsheet.
11. The regrinding case where all +1/2 inch middlings are reground and treated provided the best performance.
12. An appreciable increase of 5.7 - 6.5% in plant yield was achieved by crushing the middlings to a 1-inch top size while an increase of 4.0 - 5.4% was predicted with a ½-inch top size.
13. Improvements of up to 17-21% in ash reduction can be achieved by crushing +1/2 inch middlings at a top size of 1/2 inch.
14. Significant sulfur reductions up to 14-18% can be achieved by crushing +1/2-inch middling at a top size of 1/2 inch.
15. Substantial profit of around $10.4 million annually is projected by implementing the proposed flowsheet in present market scenario.

Appendix

A. Crushing of +1 inch middlings to various top sizes

A1. Crushing of +1 inch middlings to 1-inch top size

Table A 1 Float and sink data for 1 x 1/2-inch size fraction

Float	Incremental floats			Cumulative floats		
	Wt.%	Ash%	Sulfur%	Cum Wt.%	Cum ash%	Cum sulfur%
1.4	33.63	13.17	3.63	33.63	13.17	3.63
1.5	28.07	18.33	4.24	61.70	15.52	3.91
1.6	15.61	26.36	5.12	77.30	17.71	4.15
1.7	8.24	33.76	6.60	85.54	19.25	4.39
1.8	4.81	44.54	8.85	90.35	20.60	4.63
1.9	9.65	57.88	4.84	100.00	24.20	4.65

Table A 2 Float and sink data for 1/2 x 3/8-inch size fraction

Float	Incremental floats			Cumulative floats		
	Wt.%	Ash%	Sulfur%	Cum Wt.%	Cum ash%	Cum sulfur%
1.3	13.96	8.23	3.20	13.96	8.23	3.20
1.4	31.48	13.13	3.64	45.45	11.62	3.50
1.5	17.74	20.25	4.23	63.19	14.05	3.71
1.6	17.04	28.38	5.91	80.23	17.09	4.18
1.7	10.01	35.35	6.38	90.24	19.12	4.42
1.8	2.76	46.61	8.70	93.00	19.93	4.55
1.9	7.00	56.58	4.72	100.00	22.50	4.56

Table A 3 Float and sink data for 3/8 x 1/4-inch size fraction

Float	Incremental floats			Cumulative floats		
	Wt.%	**Ash%**	**Sulfur%**	**Cum Wt.%**	**Cum ash%**	**Cum sulfur%**
1.3	14.01	7.21	3.11	14.01	7.21	3.11
1.4	32.16	12.28	3.55	46.17	10.74	3.42
1.5	21.49	18.67	4.08	67.66	13.26	3.63
1.6	16.06	30.17	5.13	83.72	16.50	3.92
1.7	6.69	39.42	6.78	90.41	18.20	4.13
1.8	4.04	46.53	8.79	94.44	19.41	4.33
1.9	5.56	58.21	4.82	100.00	21.57	4.35

Table A- 4 Float and sink data for 6 x 1 mm size fraction

Float	Incremental floats			Cumulative floats		
	Wt.%	**Ash%**	**Sulfur%**	**Cum Wt.%**	**Cum ash%**	**Cum sulfur%**
1.3	10.68	6.59	2.96	10.68	6.59	2.96
1.4	39.20	11.21	3.42	49.88	10.22	3.32
1.5	22.23	18.67	4.02	72.11	12.83	3.54
1.6	12.38	29.91	5.28	84.49	15.33	3.79
1.7	5.07	38.53	6.58	89.56	16.64	3.95
1.8	4.22	47.53	8.58	93.77	18.03	4.16
1.9	6.23	60.13	4.55	100.00	20.65	4.18

Table A-5 Float and sink data for 1 x 0.15 mm size fraction

Float	Incremental floats			Cumulative floats		
	Wt.%	Ash%	Sulfur%	Cum Wt.%	Cum ash%	Cum sulfur%
1.3	15.46	6.32	2.91	15.46	6.32	2.91
1.4	44.00	10.79	3.27	59.47	9.63	3.18
1.5	12.88	18.52	4.24	72.35	11.21	3.37
1.6	6.23	26.42	5.14	78.58	12.42	3.51
1.7	7.21	34.5	7.27	85.79	14.27	3.82
1.8	4.76	46.72	8.97	90.54	15.98	4.09
1.9	9.46	62.32	4.59	100.00	20.36	4.14

A2. Crushing of +1 inch middlings to 1/2-inch top size

Table A-6 Float and sink data for 1/2 x 3/8-inch size fraction

	Incremental floats			Cumulative floats		
Float	Wt.%	Ash%	Sulfur%	Cum Wt.%	Cum ash%	Cum sulfur%
1.3	14.23	8.12	3.03	14.23	8.12	3.03
1.4	28.99	14.28	3.42	43.22	12.25	3.29
1.5	20.99	21.33	4.49	64.21	15.22	3.68
1.6	15.22	28.36	6.01	79.43	17.74	4.13
1.7	7.52	36.16	6.38	86.95	19.33	4.32
1.8	5.42	47.81	8.54	92.38	21.00	4.57
1.9	7.62	56.68	4.61	100.00	23.72	4.57

Table A-7 Float and sink data for 3/8 x 1/4-inch size fraction

	Incremental floats			Cumulative floats		
Float	**Wt.%**	**Ash%**	**Sulfur%**	**Cum Wt.%**	**Cum ash%**	**Cum sulfur%**
1.3	15.21	7.38	3.00	15.21	7.38	3.00
1.4	32.28	12.24	3.72	47.49	10.68	3.49
1.5	26.08	18.81	4.30	73.56	13.56	3.78
1.6	10.44	30.12	6.86	84.00	15.62	4.16
1.7	3.16	38.04	7.16	87.16	16.43	4.27
1.8	1.68	46.57	8.84	88.83	17.00	4.35
1.9	11.17	56.91	4.70	100.00	21.46	4.39

Table A-8 Float and sink data for 6 x 1 mm size fraction

	Incremental floats			Cumulative floats		
Float	**Wt.%**	**Ash%**	**Sulfur%**	**Cum Wt.%**	**Cum ash%**	**Cum sulfur%**
1.3	10.27	6.48	2.98	10.27	6.48	2.98
1.4	30.98	10.04	3.32	41.25	9.15	3.24
1.5	25.61	17.41	4.03	66.86	12.32	3.54
1.6	13.32	25.42	5.85	80.19	14.49	3.92
1.7	6.19	34.4	7.16	86.37	15.92	4.16
1.8	3.96	46.72	9.04	90.34	17.27	4.37
1.9	9.66	61.96	4.38	100.00	21.59	4.37

Table A-9 Float and sink data for 1 x 0.15 mm size fraction

	Incremental floats			Cumulative floats		
Float	**Wt.%**	**Ash%**	**Sulfur%**	**Cum Wt.%**	**Cum ash%**	**Cum sulfur%**
1.3	15.03	6.21	2.93	15.03	6.21	2.93
1.4	45.66	11.72	3.12	60.69	10.36	3.07
1.5	11.00	20.8	4.38	71.69	11.96	3.27
1.6	7.24	28.59	5.25	78.93	13.48	3.45
1.7	6.78	35.17	7.21	85.71	15.20	3.75
1.8	5.38	46.14	8.96	91.09	17.03	4.06
1.9	8.91	61.86	4.86	100.00	21.02	4.13

A3. Crushing of +1 inch middlings to 1/4-inch top size

Table A-10 Float and sink data for 6 x 1 mm size fraction

	Incremental floats			Cumulative floats		
Float	**Wt.%**	**Ash%**	**Sulfur%**	**Cum Wt.%**	**Cum ash%**	**Cum sulfur%**
1.3	10.85	6.03	3.00	10.85	6.03	3.00
1.4	26.76	10.85	3.12	37.61	9.46	3.09
1.5	26.00	17.71	4.04	63.61	12.83	3.48
1.6	15.20	27.96	5.58	78.81	15.75	3.88
1.7	8.06	36.57	6.41	86.87	17.68	4.12
1.8	5.19	45.74	8.78	92.07	19.26	4.38
1.9	7.93	62.01	4.31	100.00	22.66	4.37

Table A-11 Float and sink data for 1 x 0.15 mm size fraction

	Incremental floats			Cumulative floats		
Float	**Wt.%**	**Ash%**	**Sulfur%**	**Cum Wt.%**	**Cum ash%**	**Cum sulfur%**
1.3	13.40	6.84	2.99	13.40	6.84	2.99
1.4	46.20	10.64	3.12	59.59	9.79	3.09
1.5	11.59	18.74	3.92	71.18	11.24	3.23
1.6	8.92	24.93	5.42	80.10	12.77	3.47
1.7	7.51	33.11	7.57	87.61	14.51	3.82
1.8	4.95	46.07	8.79	92.56	16.20	4.09
1.9	7.44	62.77	4.42	100.00	19.66	4.11

A4. Crushing of +1 inch middlings to 1/8-inch top size

Table A-12 Float and sink data for 6 x 1 mm size fraction

	Incremental floats			Cumulative floats		
Float	**Wt.%**	**Ash%**	**Sulfur%**	**Cum Wt.%**	**Cum ash%**	**Cum sulfur%**
1.3	12.04	5.63	3.01	12.04	5.63	3.01
1.4	26.43	11.48	3.25	38.47	9.65	3.17
1.5	24.87	18.15	4.07	63.34	12.99	3.53
1.6	17.29	25.93	5.26	80.63	15.76	3.90
1.7	6.82	37.5	6.48	87.45	17.46	4.10
1.8	5.55	45.41	8.51	93.00	19.13	4.36
1.90	7.00	61.73	4.19	100.00	22.11	4.35

Table A-13 Float and sink data for 1 x 0.15 mm size fraction

	Incremental floats			Cumulative floats		
Float	**Wt.%**	**Ash%**	**Sulfur%**	**Cum Wt.%**	**Cum ash%**	**Cum sulfur%**
1.3	15.49	6.42	2.84	15.49	6.42	2.84
1.4	37.35	10.04	3.02	52.84	8.98	2.97
1.5	14.55	17.37	3.57	67.40	10.79	3.10
1.6	11.07	24.5	5.02	78.46	12.72	3.37
1.7	8.94	31.47	7.46	87.40	14.64	3.79
1.8	5.04	44.83	8.2	92.44	16.29	4.03
1.90	7.56	61.58	5.02	100.00	19.71	4.10

B. Crushing of 1 x ½ inch middlings to various top sizes

B1. Crushing of 1 x ½ inch middlings to ½ -inch top size

Table B 1 Float and sink data for 1/2 x 3/8-inch size fraction

	Incremental floats			Cumulative floats		
Float	**Wt.%**	**Ash%**	**Sulfur%**	**Cum Wt.%**	**Cum ash%**	**Cum sulfur%**
1.4	36.01	12.35	3.20	36.01	12.35	3.20
1.5	29.73	18.82	3.82	65.75	15.28	3.48
1.6	14.83	28.25	6.38	80.58	17.66	4.01
1.7	9.72	36.71	7.25	90.30	19.71	4.36
1.8	4.54	46.24	8.70	94.84	20.99	4.57
1.9	5.16	56.66	3.60	100.00	22.82	4.52

Table B-2 Float and sink data for 3/8 x 1/4-inch size fraction

	Incremental floats			Cumulative floats		
Float	**Wt.%**	**Ash%**	**Sulfur%**	**Cum Wt.%**	**Cum ash%**	**Cum sulfur%**
1.3	12.24	8.05	3.06	12.24	8.05	3.06
1.4	40.83	13.25	3.31	53.07	12.05	3.25
1.5	15.06	18.64	4.65	68.13	13.51	3.56
1.6	14.07	28.18	6.00	82.21	16.02	3.98
1.7	5.79	38.92	6.38	88.00	17.53	4.14
1.8	4.66	46.74	8.92	92.66	19.00	4.38
1.9	7.34	57.86	3.80	100.00	21.85	4.33

Table B-3 Float and sink data for 6 x 1 mm size fraction

	Incremental floats			Cumulative floats		
Float	**Wt.%**	**Ash%**	**Sulfur%**	**Cum Wt.%**	**Cum ash%**	**Cum sulfur%**
1.3	10.16	5.92	2.90	10.16	5.92	2.90
1.4	25.37	10.52	3.07	35.53	9.21	3.02
1.5	26.90	17.3	4.12	62.43	12.69	3.49
1.6	18.52	26.55	5.02	80.95	15.86	3.84
1.7	6.54	35.29	7.98	87.49	17.32	4.15
1.8	4.58	45.02	9.08	92.07	18.69	4.40
1.9	7.93	63.87	4.26	100.00	22.28	4.39

Table B-4 Float and sink data for 1 x 0.15 mm size fraction

	Incremental floats			Cumulative floats		
Float	**Wt.%**	**Ash%**	**Sulfur%**	**Cum Wt.%**	**Cum ash%**	**Cum sulfur%**
1.3	15.15	6.82	2.98	15.15	6.82	2.98
1.4	46.79	12.36	3.09	61.94	11.00	3.06
1.5	11.64	19.11	4.47	73.58	12.29	3.29
1.6	9.59	25.11	5.83	83.17	13.77	3.58
1.7	6.07	34.74	7.79	89.24	15.19	3.87
1.8	3.96	46.94	9.04	93.21	16.54	4.09
1.9	6.79	62.27	4.42	100.00	19.65	4.11

B2. Crushing of 1 x 1/2 inch middlings to 1/4-inch top size

Table B-5 Float and sink data for 6 x 1 mm size fraction

	Incremental floats			Cumulative floats		
Float	**Wt.%**	**Ash%**	**Sulfur%**	**Cum Wt.%**	**Cum ash%**	**Cum sulfur%**
1.3	11.56	6.42	2.98	11.56	6.42	2.98
1.4	26.94	11.06	3.44	38.50	9.67	3.30
1.5	23.85	17.18	4.03	62.35	12.54	3.58
1.6	14.92	24.04	5.20	77.27	14.76	3.89
1.7	8.85	32.05	6.12	86.12	16.54	4.12
1.8	4.81	45.70	8.94	90.93	18.08	4.38
1.9	9.07	61.76	4.40	100.00	22.04	4.38

Table B-6 Float and sink data for 1 x 0.15 mm size fraction

	Incremental floats			Cumulative floats		
Float	**Wt.%**	**Ash%**	**Sulfur%**	**Cum Wt.%**	**Cum ash%**	**Cum sulfur%**
1.3	16.87	6.03	2.95	16.87	6.03	2.95
1.4	43.15	12.30	3.23	60.02	10.54	3.15
1.5	11.75	20.33	4.07	71.76	12.14	3.30
1.6	9.97	26.11	5.15	81.74	13.85	3.53
1.7	6.96	34.16	7.58	88.70	15.44	3.85
1.8	4.64	46.81	9.04	93.34	17.00	4.10
1.9	6.66	63.82	4.31	100.00	20.12	4.12

B3. Crushing of 1 x 1/2 inch middlings to 1/8-inch top size

Table B-7 Float and sink data for 6 x 1 mm size fraction

	Incremental floats			Cumulative floats		
Float	**Wt.%**	**Ash%**	**Sulfur%**	**Cum Wt.%**	**Cum ash%**	**Cum sulfur%**
1.3	11.21	6.13	2.87	11.21	6.13	2.87
1.4	27.81	12.28	3.31	39.02	10.51	3.18
1.5	22.87	18.15	4.15	61.89	13.34	3.54
1.6	15.95	22.84	5.05	77.83	15.28	3.85
1.7	8.34	32.28	6.47	86.17	16.93	4.10
1.8	4.47	40.2	8.34	90.64	18.07	4.31
1.90	9.36	62.21	4.17	100.00	22.21	4.30

Table B-8 Float and sink data for 1 x 0.15 mm size fraction

	Incremental floats			Cumulative floats		
Float	**Wt.%**	**Ash%**	**Sulfur%**	**Cum Wt.%**	**Cum ash%**	**Cum sulfur%**
1.3	16.38	5.95	2.91	16.38	5.95	2.91
1.4	42.18	11.32	3.02	58.55	9.82	2.99
1.5	13.21	20.17	4.19	71.76	11.72	3.21
1.6	9.60	25.42	6.2	81.36	13.34	3.56
1.7	7.56	31.95	7.46	88.92	14.92	3.89
1.8	5.24	48.33	8.94	94.15	16.78	4.17
1.90	5.85	62.98	4.05	100.00	19.48	4.17

C. Crushing of ½ x ¼ inch middlings to various top sizes

C1. Crushing of ½ x ¼ inch middlings to ¼ -inch top size

Table C 1 Float and sink data for 6 x 1 mm size fraction

	Incremental floats			Cumulative floats		
Float	**Wt.%**	**Ash%**	**Sulfur%**	**Cum Wt.%**	**Cum ash%**	**Cum sulfur%**
1.3	11.53	6.23	3.01	11.53	6.23	3.01
1.4	24.00	10.45	3.11	35.53	9.08	3.08
1.5	25.54	16.56	3.74	61.07	12.21	3.35
1.6	16.17	24.69	5.12	77.24	14.82	3.72
1.7	8.14	32.92	6.79	85.38	16.55	4.02
1.8	5.99	46.67	9.01	91.36	18.52	4.34
1.9	8.64	61.21	4.17	100.00	22.21	4.33

Table C-2 Float and sink data for 1 x 0.15 mm size fraction

	Incremental floats			Cumulative floats		
Float	**Wt.%**	**Ash%**	**Sulfur%**	**Cum Wt.%**	**Cum ash%**	**Cum sulfur%**
1.3	14.27	6.42	3.06	14.27	6.42	3.06
1.4	48.49	12.32	3.21	62.76	10.98	3.18
1.5	13.54	20.33	4.87	76.31	12.64	3.48
1.6	7.46	26.36	6.25	83.77	13.86	3.72
1.7	6.36	34.16	6.63	90.13	15.29	3.93
1.8	3.51	47.81	8.89	93.64	16.51	4.11
1.9	6.36	62.28	5.22	100.00	19.42	4.18

C2. Crushing of ½ x ¼ inch middlings to 1/8 -inch top size

Table C-3 Float and sink data for 6 x 1 mm size fraction

Float	Incremental floats Wt.%	Incremental floats Ash%	Incremental floats Sulfur%	Cumulative floats Cum Wt.%	Cumulative floats Cum ash%	Cumulative floats Cum sulfur%
1.3	12.55	6.31	2.93	12.55	6.31	2.93
1.4	23.56	11.23	3.14	36.11	9.52	3.07
1.5	25.56	18.52	3.44	61.67	13.25	3.22
1.6	15.63	23.11	5.17	77.30	15.24	3.62
1.7	7.96	30.64	6.42	85.26	16.68	3.88
1.8	6.64	42.08	8.95	91.90	18.52	4.24
1.90	8.10	62.42	4.09	100.00	22.07	4.23

Table C-4 Float and sink data for 1 x 0.15 mm size fraction

Float	Incremental floats Wt.%	Incremental floats Ash%	Incremental floats Sulfur%	Cumulative floats Cum Wt.%	Cumulative floats Cum ash%	Cumulative floats Cum sulfur%
1.3	13.45	6.29	2.88	13.45	6.29	2.88
1.4	43.47	11.65	3.11	56.91	10.38	3.06
1.5	18.31	19.65	4.29	75.22	12.64	3.36
1.6	7.80	25.14	5.68	83.02	13.81	3.57
1.7	6.18	34.69	6.72	89.20	15.26	3.79
1.8	4.26	42.51	8.93	93.47	16.50	4.03
1.90	6.53	61.79	5.31	100.00	19.46	4.11

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