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PILOT SCALE DEMONSTRATION AND EVALUATION OF INNOVATIVE NON-DESLIMED NON-CLASSIFIED GRAVITY-FED HM CYCLONE

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PILOT SCALE DEMONSTRATION AND EVALUATION OF INNOVATIVE NON-DESLIMED NON-CLASSIFIED GRAVITY-FED HM CYCLONE

THESIS

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

By

Yumo Zhang

Lexington, Kentucky

Director: Dr. Rick Q. Honaker, Professor of Mining Engineering

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2015

ABSTRACT OF THESIS

PILOT SCALE DEMONSTRATION AND EVALUATION OF INNOVATIVE NON-DESLIMED NON-CLASSIFIED GRAVITY-FED HM CYCLONE

Coal preparation plants are required in some cases to produce a high-grade product using a low specific gravity cut-point. For these situations, a second higher gravity separation would be desirable to generate a mid-grade product that can be utilized for electricity generation thereby maximizing coal recovery. A study was conducted to evaluate the potential of achieving efficient separations at two different density cut-points in a single stage using a three-product dense medium cyclone. Variations in density cut-point and process efficiency values were quantified as a function of the feed medium density, feed medium-to-coal ratio, and feed pressure using a three-level experimental design program. Results indicate the ability to effectively treat coal over a particle size range from 6mm to 0.15mm while achieving both low- and high-density cut-points up to 1.95 relative density. Ash content decreased from 27.98% in the feed to an average of 7.77% in the clean coal product and 25.76% in the middlings product while sulfur content was reduced from 3.87 to 2.83% in the clean coal product. The overall combustible recovery was maintained above 90% while producing clean coal products with ash and total sulfur content as low as 5.85 and 2.68%, respectively. Organic efficiency values were consistently about 95% and probable error values were in the range of 0.03 to 0.05, which indicates the ability to provide a separation performance equivalent to or better than traditional coal cleaning technologies.

Keywords: Dense Medium Cyclone, Three Products, Fine Coal Separation, Parametric Evaluation, Tracer Tests.

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Date

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Date

DEDICATION

This work is dedicated to my mother Yan Lin, my father Zhigang Zhang, and all my family members and friends for their everlasting love, support and trust.

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1. CHAPTER 1 – INTRODUCTION

1.1. Executive Summary

In a typical coal preparation plant, raw coal is crushed to 50-150 mm (2-6 inch) top size; then classified by size and deslimed into plus 6 mm (+1/4 inch) coarse fraction, 6 × 1 mm (1/4 inch × 16 mesh) intermediate fraction, 1 × 0.5 mm (16 × 100 mesh) fine fraction, and minus 0.15 mm (-100 mesh) ultrafine fraction to maximize the efficiency of upgrading coal quality to meet contract specifications. In the Illinois Basin, approximately 85% of the plant feed consists of material in the coarse and intermediate size fractions, which are treated by dense medium vessels and cyclones, respectively, or by a single-stage dense medium cyclone circuit. The fine fraction is upgraded by spiral concentrators while the ultrafine fraction is treated by froth flotation.

To simplify the conventional process as well as to improve efficiency, an innovative non-deslimed, non-classified gravity-fed three-product dense medium (DM) cyclone was evaluated in this research project. The innovative three-product cyclone consists of a cylindrical first stage and a conical second stage. The DM suspension enters the cylindrical cyclone tangentially under pressure at one end whereas the raw coal is fed axially to the center of the cyclone by gravity at the other end, which is in sharp contrast with the conventional DM cyclone into which coal and DM suspension are fed together as a mixture under pressure. Light particles remain near the air core in the center and are discharged as clean coal through the overflow pipe whereas heavy material moves toward the wall of the cylindrical cyclone under the action of centrifugal force and quickly discharges into the conical cyclone through the overflow orifice, minimizing wear to the cyclone wall. During this separation process, only the heavy material moves radially through the separation zone, minimizing interferences between light and heavy particles that move in opposite directions in a conventional cyclone where coal is fed tangentially in a mixture with the heavy medium. This improvement in the separation environment inside the cyclone results in a higher separation efficiency and a lower loss of clean coal. The medium suspension in the cylindrical cyclone underflow that enters the conical cyclone has a significantly higher density than the original DM density as a result of thickening and size classification in the cylindrical cyclone. This creates a much higher density of separation in the conical cyclone than the original DM density without using a denser, *i.e.*, more costly, heavy medium to reject pure rocks with a minimum loss of coal.

A systematic study was performed using a pilot-scale three-product DM cyclone (8-inch or 200-mm in diameter) manufactured by Guohua Technology Corporation (GTC) with a capacity of 8-12 tons per hour (tph) under controlled process conditions to investigate effects of major process parameters on separation performance and identify optimum conditions for treating Illinois Basin coal. Process parameters examined include feed pressure, medium-to-coal ratio, and medium specific density. The optimum condition was identified by conducting a total of 15 tests using three-factor, three-level Box-Behnken experimental design. Each stream produced under the optimum condition was sampled and subjected to a particle size-by-size float-sink analysis to determine how performance changes with particle size as well as slime content. Probable error (Ep) values achieved with the 6 × 1 mm (1/4-inch × 16 mesh) size fraction were 0.04, 0.03, and 0.045 in the first stage and 0.03, 0.05, and 0.035 in the second stage while varying slime (-0.15 mm) concentration in the feed at 0%, 10%, and 20% by weight, respectively. For 1 × 0.15 mm particles, Ep values were 0.1, 0.04, and 0.05 in the first stage and 0.04, 0.055, and 0.04 in the second stage over the same range of slime concentrations. Organic efficiency values for both 6 × 1 mm and 1 × 0.15 mm size fractions exceeded 95% and were above 99% under most conditions. Considering that the Ep range for a typical spiral is 0.12-0.18 and the organic efficiency is 85-90%, these results indicate an obvious advantage of the innovative three-product cyclone compared with spirals and thus show the possibility of eliminating the fine circuit (1 × 0.15 mm) and feeding by zero.

One strength of the three-product DM cyclone is the ability to produce a high-quality clean coal product and a medium quality product, which ensures maximum recovery of energy-producing combustibles in the feed coal. Illinois Basin operators are often requested to provide clean coal having a total sulfur content that requires a low-density cut-point below 1.5 relative density (RD). For a two-product system, the low-density separation would result in a significant loss of valuable middlings material, which could be captured in a three-product separator. A detailed investigation was conducted to evaluate the difference in the density cut-points achieved in both first and second stages of the GTC cyclone unit and to determine those mechanisms needed to control the difference in an effort to target specified clean coal and middlings product qualities. Cubic tracer blocks measuring 10 mm in all dimensions and having RDs between 1.3 and 2.0 were used to assist in the assessment.

As expected, the feed medium density and pressure were found to be important factors that directly control the density cut-point in both stages of the GTC three-product cyclone. At low densities, the medium becomes somewhat unstable in the first stage, which elevates the feed medium density to the second stage. An increase in feed pressure decreases the medium stability further and raises the cut-point in the second stage. When testing a medium density of 1.4 RD under the lowest feed pressure, the density cut-point in the first stage was 1.535 RD while the cut-point in the second stage was 1.65 RD, an offset differential of 0.115 RD. When the feed pressure was increased to the highest level, the first stage cut-point decreased significantly to 1.455 RD due to the greater medium instability while the corresponding second stage cut-point increased to 1.75 thereby creating a differential of nearly 0.30 density units. A feed medium density of 1.6 RD was significantly more stable reducing the cut-point differential between the two cleaning stages to approximately 0.20 density units at the highest feed pressure. These results clearly show the dependency of test conditions on the interplay between first and second stage separation performance in the GTC three-product separator.

Test results presented in this work clearly indicate that the GTC three-product separator has the ability to provide efficient upgrading of Illinois Basin coal by producing a clean coal product that meets high-quality specification requirements while also producing a medium quality product that can be used in the utility market. The separation efficiency is equivalent to two-product DM cyclones for coarse particle size fractions and superior to the performance provided by traditional technologies used to treat fine fractions.

1.2. Introduction and Background

The dense medium cyclone (DMC) is the most popular technology used worldwide for upgrading the quality of ROM coal in the particle size range between 75 and 1 mm. The process utilizes a medium formed by a mixture of water and ultrafine magnetite particles. Medium density is adjusted to obtain a cut-point value that provides the desired product quality. Typically, 75 × 1 mm ROM coal is added to the medium and pumped under a desired pressure to the DMC. This feed enters the cyclone tangentially creating a centrifugal force of sufficient magnitude to provide highly efficient separation performances over a relatively large range of particle sizes. The conventional DMC produces a clean coal product in the overflow stream and reject in the underflow stream.

Throughout the later part of the twentieth century, DMC design was largely based on the Dutch State Mines (DSM) criteria. As shown in Figure 1.1, feed enters into a cylindrical barrel having a diameter that typically defines the particle size range and capacity of the cyclone. The barrel length is 50% of the barrel diameter. The maximum particle size treatable for the cyclone is controlled by the inlet diameter, which is 20% of the barrel diameter. The heavy medium and feed coal moves downward through the barrel into a conical portion of the cyclone, which has an included angle of 20 degrees. Reject and medium near the walls of the cone pass through an apex that has a diameter dependent on the desired volume yield to the underflow stream. This is typically in the range of 30 to 40% of the barrel diameter. The clean coal and about 67% of the medium reverses vertical direction in the cone and moves upward into the vortex finder that extends through the top of the cyclone in an inverted U-shape to a point slightly below the feed port. The vortex finder diameter is 43% of the cyclone barrel diameter. With this geometric design, throughput capacities of a few hundred tons per hour can be achieved treating 6 × 1 mm (1/4-inch × 16 mesh) coal while achieving separation efficiencies far superior to any other coal cleaning technology. Probable error values (*Ep* = $[\rho_{25} - \rho_{75}]/2$) reported from industrial installations are typically in the range of 0.01 to 0.03.

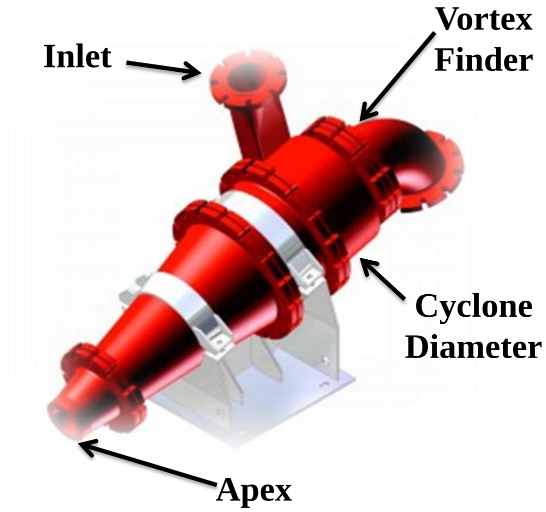

Figure 1.1: Typical DMC design.

Since the mid-1990s, DMC cyclone design has moved away from the original DSM criteria to allow for processing of higher throughput capacities per unit thereby reducing impacts of feed distribution on process efficiency. The inlet diameter has increased to 30% or more of the cyclone diameter which has also resulted in the ability to treat particles as coarse as 75 mm. For most operations in the Illinois Basin, the larger particle size material represents 80-85% of the plant feed. The ability to treat coarser material has allowed for elimination of the DM vessel circuit, which reduces capital and operating costs significantly.

As previously described, the traditional DM cyclone is a two-product separator that generates a clean coal product and a reject. In some cases, it is necessary to achieve relative density separations that are below 1.5 RD. For the Illinois Basin, this situation may be required to generate an acceptable total sulfur content to meet a contract specification. To avoid significant coal losses at the low-RD cut-point, a second DMC unit would be considered to make a higher density separation (*e.g.*, 1.7 RD) that would produce a medium total sulfur content coal for selling in a lower value market. The added DMC unit would require additional equipment beyond the second DMC, such as a pump and sump. An alternative approach is to use a single-stage, three-product DMC unit, which is the focus of the investigation that led to this research.

<u>Innovative Three-Product Dense Medium Cyclone</u>

The research involved the demonstration and evaluation of an innovative non-desliming, gravity-fed DMC applied to upgrading Illinois Basin coals. Guohua Technology Corporation (GTC) is the commercial marketer of the technology, which is distributed through the Daniels Company, an American subsidiary. The GTC DMC unit is used in over 500 coal preparation plants in China (Zhao et al., 2010; Zhao and Yu, 2012).

As schematically illustrated in Figure 1.2, the GTC three-product DM cyclone consists of a first-stage cylindrical unit and a second-stage cylindro-conical unit, which are connected in series. Only the medium suspension enters the first-stage cyclone tangentially under a

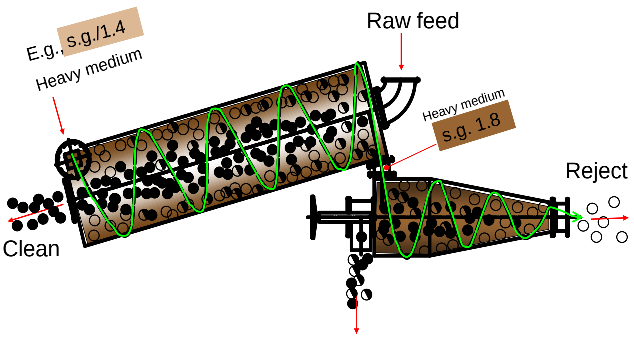

Figure 1.2: Schematic of the GTC three-product DMC.

desired pressure while the raw coal is injected axially at the top end by gravity. The rotating medium creates an open vortex centrally located along the length of the cylinder. Under the effect of centrifugal force and the medium density, the light material (coal) moves toward the air core and is discharged along with the central air core through the underflow tube at the bottom without coming into contact with cyclone wall. This is advantageous in that it reduces wear in the inlet area and along the cylinder walls. The heavy (and generally abrasive) material settles through the medium under the influence of the centrifugal force and immediately exits the cylinder via the upper tangential sink outlet where it enters the second-stage cyclone under the influence of the axial velocity of the outer spiral flow. As such, only the near gravity particles separated further along the unit axis actually come into contact with the cylinder body, which also minimizes wear on the unit. The medium suspension that goes into the second-stage cyclone is subjected to thickening and size classification under the influence of centrifugal force in the cylinder and thus contains higher magnetite concentration than the original heavy medium. This creates a favorable density separation condition for heavy materials that move from the cylindrical cyclone into the cylindro-conical cyclone, which is essentially a DSM style cyclone.

One of the unique features of the GTC three-product DMC compared to other cylindrical cyclone technologies such as the Dynawhirlpool and Larcodem cyclones is lack of a vortex finder for the clean coal discharge typically located in the center of a cylindrical DMC unit. The advantage of this is an increase in particle retention time resulting in reduced contamination by fine refuse in the clean coal and improved separation precision. An additional advantage over traditional DMC units is the separate feed entrances for the medium and coal. As a result, only heavy material moves radially outward across the "separating cone" whereas, in a conventional cyclone, both heavy and light materials move radially across the "separating cone" causing mutual interference. Also, on-line adjustment of the separation density achieved in the second-stage cyclone can be achieved by varying insertion depth of the vortex finder, which is made to be controllable.

Commercial GTC units are described on the basis of diameter values of the cylinder and cylindro-conical component units. A 3GDMC specification of 1400/1000, as shown in Figure 1.3, indicates that the first stage cylinder unit has a diameter of 1400 mm and the second stage unit has a diameter of 1000 mm. The throughput capacity of the unit is around 500tph of material having a maximum top size of 100 mm (4 inches). Industrial performance data indicates a typical separation performance that includes a RD cut-point of 1.430 in the first stage and 1.683 in the second stage. Ep values in the first stage ranged from 0.025 to 0.034 and were somewhat higher in the second stage at 0.050 to 0.065 due to viscosity effects. Organic efficiency values (*i.e.*, actual yield ÷ theoretical yield) are reportedly greater than 95%.

Figure 1.3: Photograph of a commercial-scale GTC three-product DMC.

1.3. Research Goals and Objectives

The overall goal of this research program was to demonstrate the cleaning potential and evaluate the separation performance of the innovative non-deslimed, non-classified, gravity-fed dense medium cyclone developed by Guohua Technology Corporation (GTC) when applied to the treatment of Illinois Basin coal. The specific project objectives were:

1. Design, fabricate, and operate a pilot-scale GTC dense medium cyclone system with a capacity of up to 12 tons per hour (tph)(Tasks 1, 2, and 3);

2. Perform a parametric study to provide an understanding of the process when cleaning Illinois Basin coal (Task 4);

3. Achieve optimized separation and efficiency performance for Illinois Basin coal when processing it using the novel three-product dense medium cyclone (Task 4).

1.4. Statement of Work

1.4.1. Task 1. Site selection and feed acquisition/characterization

An appropriate pilot scale testing site was selected for the erection and operation of the pilot scale GTC cyclone system for cleaning non-deslimed and un-sized raw coal. It must have a sufficient space (approximately 25’ × 25’ × 20’) for the cyclone separation system and have a power and water supply; must be able to store and dispose of separated products.

After the testing site was selected, typical Illinois Basin coal samples were acquired from the willow lake coal preparation plant located in Southern Illinois. A total number of 1500 pounds of dense medium cyclone feed samples was acquired for the pilot scale testing program. Once arrived, the coal samples were crushed and thoroughly mixed. A representative sample was taken for size distribution analysis and approximate analysis. Unlike a typical lab or pilot scale system for fine particles, this designed pilot scale cyclone system operates at a high capacity, approximately 8 TPH. To reduce the required amount of coal needed for the testing, most of the tests conducted in this program were performed at a feed rate lower than its capacity and coal samples were re-used whenever possible.

1.4.2. Task 2. Engineering design and construction of the pilot scale system

Based on the previous laboratory study and commercial practices of the GTC cyclone technology in China, the engineering design and fabrication was undertaken to produce a pilot scale GTC cyclone testing system with a diameter of 8” and a capacity of about 8 TPH. The pilot scale system primarily consists of an 8”-diameter GTC cyclone, a heavy medium pump, a 180-gallon sump, pipes, mixers and auxiliary components. The system was fabricated and supplied by GTC.

1.4.3. Task 3. Installation and shakedown

This task covers the functions necessary to install and start up the pilot scale GTC cyclone system. University of Kentucky (UK) Mining engineering personnel worked with GTC staff in transporting and installing the system for testing, demonstration and evaluation. The collaborating company GTC provided cost-sharing efforts of off-loading the pilot-scale system, lifting and locating the unit to the pre-selected site, and hooking up the power, water, feed, product and tailings connections. A start-up and shakedown procedure for the system were prepared and implemented. Exploratory no-load testing of the system was performed with the heavy medium only to examine the system function and dependability before coal is fed to the system.

1.4.4. Task 4. System operation and detailed parametric testing

The pilot scale cyclone system was operated under different conditions to evaluate the separation performance and effects of various process parameters. Major operating parameters to be examined in this task include heavy medium density (1.4, 1.5, 1.6 sp.gr), heavy medium feed pressure (9, 12, 15 times diameter of the cyclone), and medium-to-coal ratio (3:1, 4:1, 5:1). The separation performance was evaluated in terms of clean coal and reject ash and recovery, separation S.G., organic separation efficiency, probable error, and by-pass on a particle size-by-size basis. Density differential between overflow and underflow was determined to understand the medium stability and its influence on performance. To determine the Ep value, clean coal and reject products were collected and subjected to float and sink analysis using non-toxic, non-volatile heavy liquid lithium metatungstate (LMT). The results from these tests are essential for identification of the proper range of operating parameters for the optimization studies in Task 5.

1.4.5. Task 5. System Optimization

A multiple factor three level Box-Behnken statistical experimental design was carried out to optimize individual process variables and evaluate their interactions. The high- and low-levels (+1 and -1) of parameters such as medium-to-coal ratio, heavy medium density and heavy medium feed pressure were determined based on experimental results from Task 4. The most significant variables and optimum conditions were established from statistical analysis of the experimental results using response surface methodology (RSM). The Box-Behnken experimental design and subsequent RSM analysis were conducted using a sophisticated software Design-Expert 5.09® acquired from Stat-Ease Inc., Minneapolis, MN. The separation performance data obtained from this task was compared with those produced from conventional cyclone separators to demonstrate the performance advantages of the proposed technology. Sample collection and characterization studies similar to those in Task 4 were carried out for each test. The clean coal and reject samples produced under the optimum conditions were subjected to a size-by-size float and sink analysis to determine how the separation performance (Ep value, separation efficiency, etc) changes with particle size and the slime impact.

2. CHAPTER 2 – LITERATURE REVIEW

2.1. Background of Heavy Medium Cyclone Technology

Sizing and desliming of raw coal feed is usually required for the conventional heavy medium coal preparation process. In a typical coal preparation plant, the raw coal is usually crushed to a top size of 5-6 in. This material then passes over wet sizing screens which generally size at 3/8 in. or ¼ in. Large size lump coal (+3/8 or ¼ in.) is processed with the heavy medium vessel or other heavy medium separators. The fine raw coal (-3/8 or ¼ in.) which has passed through the wet sizing screens is fed to a fixed sieve-bend screen which normally separates at 0.5 mm. The reasons for desliming at 0.5 mm are: 1) the 0.5 mm is the smallest particle that can be easily rinsed on vibrating screens without excessive loss of magnetite and without blinding the sieve bend and vibrating screen decks; 2) to avoid excessive contamination of the medium with non-magnetic coal or clay fines. The most undesirable contaminant is the sub-micron size clay particles that greatly increase the viscosity of the medium (Napier-Munn, 1980). The oversize (3/8 or ¼ in. - 0.5 mm) is next passed over a vibrating screen where water sprays aid in removing the remaining -0.5 mm material. The deslimed raw coal is fed to a head tank where it is mixed with the dense medium and this mixture is pumped to the cyclone which operates with inlet pressure as low as 6-8 psi (1 psi = 0.07 kg/cm^2) and as high as 20 psi (1.4 kg/cm^2) or more although 10-14 psi (0.7-1.0 kg/cm^2) is a good average. The overflow, which contains the washed coal, flows to a sieve-bend screen and then to a vibrating drain and rinse screen to remove the magnetite from coal. The dilute medium (predominately magnetite and rinse water, but containing some nonmagnetic material) flows to a magnetic separator which recovers and concentrates the magnetite. The magnetic separator also removes the nonmagnetic particles (fine coal and clay) which would otherwise accumulate in the dense medium and cause excessive viscosity of the dense medium which is detrimental to the separation performance. The underflow from the cyclone, which contains the refuse, is processed similarly. The dilute medium from the overflow and underflow often flows to the same magnetic separator for separation and concentration.

It should be noted that in a typical heavy medium cyclone flowsheet smaller size coal, *i.e.*, 3/8 or ¼ in. - 0.5 mm fraction, is processed after desliming using a single or two stages of H.M. cyclones with a single or double (high and low) densities of heavy media. Oftentimes coarse fine coal (nominally 1-0.15 mm) is processed with a spiral, TBS, or similar separators (Honaker and Forrest, 2003). This traditional heavy medium flowsheet is not only complicated but also low in separation efficiency with the coarse fine coal. In some cases no specified clean coal product can be produced with difficult-to-wash coals with a reasonable recovery. In addition, the high lower size limit of separation for the spiral or TBS results in a large amount of coal fines entering the relative high cost and low efficiency flotation operation.

The innovative high-efficiency and simplified GTC HM cyclone technology uses a single separator to replace three to five devices that include primary (and secondary) separator(s) for lump coal, primary (and secondary) 2-product cyclone(s), and coarse fine coal separators such as spiral or TBS. The recently developed unique heavy medium cyclone does not require desliming and sizing of raw coal feed and simultaneously produces three products including clean coal, middlings and reject using a single low density heavy medium suspension. It eliminates the use of instable and difficult to prepare high-density HM suspension when the required separation density is higher than 1.7 kg/L. This unique cyclone can certainly produce two products (clean coal and reject) with higher separation efficiency than conventional cyclones by combining the middlings with either clean coal or reject or directly by using the cylindrical cyclone when appropriate. The proposed heavy medium process not only considerably simplifies the process flowsheet but also significantly improves separation efficiency. In addition, the new process solves the problem that pure reject cannot be produced at high separation density (>1.8 kg/L) for some coals when heavy medium vessels or other H.M. separators or 2-product cyclones are employed.

2.2. Principle of Traditional Heavy Medium Cyclone

In a typical heavy medium cyclone, the mixture of heavy medium and raw coal enters tangentially near the top of the cylindrical section, thus forming a strong vertical flow. The refuse moves along the wall of the cyclone and is discharged through the underflow orifice. The washed coal moved toward the longitudinal axis of the cyclone and passes through the vortex finder to the overflow chamber.

In a heavy medium cyclone, the magnitude of the centrifugal and buoyant forces that separate the particles governs the velocity with which the particles separate, which in turn determines the capacity of the cyclone. The net centrifugal force may be written as follows:

$$F_c = (M_p - M_f)\frac{V^2}{r} = \frac{1}{6}\pi d^3(\rho_p - \rho_f)\frac{V^2}{r}$$

Where F_c is centrifugal force, M_p is mass of particle, M_f is mass of fluid, V is tangential velocity, r is radius of cyclone, d is particle diameter, ρ_p and ρ_f are density of particle and fluid, respectively.

The centrifugal force will be balanced by the resistance of the liquid when terminal velocity is reached. For small forces when ρ_p and ρ_f are close to each other, the particles fall in the Stoke's range where the fluid resistance is essentially due to viscosity. For large forces, however, the particles will fall in the Newton's range where the fluid resistance is primarily inertial and substantially independent of viscosity. Thus, it is impossible to write an exact equation for the terminal velocity that is applicable to all particles. Nevertheless, it is apparent that the forces causing the particles to separate in a cyclone are proportional to V^2/r, which is more than 20 times greater than the gravitation force. In the conical section of the cyclone, V is further increased according to the following relationship (Krijgsman, 1952):

$$Vr^{1/2} = \text{constant}$$

At the apex of the cyclone the acceleration increases to over 200 times greater than gravity. Thus, the forces tending to separate the coal and impurity particles are much greater in a cyclone than in a static bath. This offers two advantages: 1) it accounts for the relatively large capacity of the cyclone; 2) because these forces acting on even the smallest particles are much larger, the cyclones is much more applicable for cleaning fine coal.

An important factor that influences the separation in a cyclone is the progressive increase in specific gravity of the medium as it descends toward the apex. This increase occurs because the centrifugal force tends to force the medium particles toward the cyclone wall. Thus, the specific gravity of the medium flowing through the underflow orifice is higher than that of the feed medium whereas the specific gravity of the medium passing through the overflow orifice is lower. The heavy medium cyclones employed for coal washing usually operate at a minimum feed pressure of at least 9 times the cyclone diameter D in meters of liquid column. Larger diameters cyclones treating wider size ranges of coal may require far higher feed pressures than 9D. The usual range of pressure for heavy medium cyclone is from 0.4 to 0.8 kg/cm^2 (Deurbrouck and Hudy, 1972; Vanangamudi and Rao, 1987).

Matsuno (1960) used heavy medium cyclone and other devices to clean up to 25 mm and down to 0.5 mm coal particles 3at a coal mine. He concluded that cyclone was the most efficient unit for cleaning fine coal down to about 48 mesh, especially if feed was difficult to treat. Sokaski and Geer (1963) built and tested a 5 TPH dense-medium cyclone pilot plant to clean 1/2 in. to 0 size coal without removal of extremely fine material from feed. Tests with four different raw coals and one crushed jig middling product indicated that the magnetite loss averaged about 2.5 lb/ton of feed and the cleaning performance of cyclone was influenced by several factors. Stoessner et al. (1988) conducted extensive commercial testing and their results also clearly demonstrated that heavy medium cyclones are the most effective process for cleaning a 0.6 × 0.15 mm (28 × 100 Mesh) coal. They also described the type of circuitry required to maximize performance.

2.3. Types of Cyclones

There are two principal cyclone systems for dense medium separation (Van der Walt and Venter, 1975; Wills and Lewis, 1980; Collins, 1988; Ferrara, 1995; Majumder et al., 2006; Huo et al., 2011). The standard cyclone geometry is exemplified by the Dutch State Mine (DSM) cyclone which consists of an inverted hollow conical portion joined to a cylindrical section at the top (Krijgsman, 1952; Matsuno, 1960), which is very similar to classification cyclones but with much larger orifice/cyclone diameter ratios. The second type of cyclone includes the Dyna-whirlpool (DWP), the Tri Flo and the Larcodems separators (Polhemus and Ammon, 1966; Fleming, 1975; Wills and Lewis, 1980; Abbot et al., 1996; Majumder et al., 2006). These separators have a cylindrical body that is inclined about 25^o from the horizontal. The medium is pumped independently to coal tangentially to the lower segment of the inclined cyclone. A vortex with a central air core is formed in the cylinder. Coal is fed axially to the top part of the cyclone and is entrained in the rotating vortex. The heavy particles migrate toward the wall and are discharged through a tangential outlet near the upper end of the cylinder with a controlled back pressure. The washed coal stays near the air core and is discharged axially through a central opening in the bottom end of the cylinder. The control of the back pressure on the sinks (tailings) discharge is achieved normally with a pipe discharge loop on the DWP, with an adjustable sinks discharge box on the Tri Flo and with a vortex-tractor on the Larcodems which is also used on the Vorsyl cyclone (Wills and Lewis, 1980; Abbot et al., 1996; Majumder et al., 2006).

With the second type of cyclone such as DWP cyclone (a typical length to diameter ratio is 4 or 5:1), only the circulating medium is pumped into the lower tangential opening and the coal is fed to the upper part of DWP cyclone by gravity. Thus the generation of secondary coal fines is minimized. Since the sink product immediately leaves the cyclone through the upper port while the float or coal moves toward the center and is discharged from the lower end, most of particle contacts with the wall of cyclone are avoided. Therefore, a practical advantage of the second type of cyclone is that wear on the cyclone inlet and the walls of the cyclone is substantially reduced, particularly where a vast majority of feed is coal. It has been reported that the DWP heavy medium cyclone with a diameter as large as 1.5 m cleans coal effectively and energy-efficiently (Wills and Lewis, 1980; Huo et al., 2011).

Majumder et al. (2006) performed a comparative study on magnetite medium stability in a Vorsyl separator (VS) and in a heavy medium cyclone (HMC) and found that the differential between the underflow and overflow slurry density is always less in a VS than in a HMC. They concluded that more stable medium in VS contributes to its better performance than HMC when treating coals with high near-gravity material, which is consistent with previous studies of dense medium stability and viscosity on the separation sharpness of HMC (Napier-Munn, 1980; Ferrara, 1995). They believe that better stability of heavy medium in a VS is a result of the constant centrifugal force. In contrast, the centrifugal force changes in a HMC since the diameter changes from the cylinder to the cone. It is recognized (Ferrara, 1995; Abbot et al., 1996; Majumder et al., 2006) that the recovery of low specific gravity material and the rejection of impurity is noticeably improved at higher pressures, especially for finer sizes.

2.4. Process Simulation

Rao et al. (1986) and Napier-Munn (1991) developed mathematical models for and performed numerical simulation of heavy medium cyclone separation processes. Natasimha et al. (2007) developed a computational fluid dynamics (CFD) model of the dense medium cyclone (DMC) using Fluent by coupling component models for the air-core, the magnetite medium and coal particles. Multiphase simulations (air/water/medium) using the large Eddy simulation (LES) turbulence model, together with viscosity corrections according to the feed particle loading factor, gave accurate predictions of axial magnetite segregation, with results close to gamma ray tomography data. Liu et al. (2009) carried out the numerical simulation of the flow fields in the gravity-fed 3-product H.M. cyclone with a diameter of 1000/700 mm based on SKE/DRSM turbulent flow model in Fluent. They also established three-dimensional velocity, density and pressure distribution of the flow field within the cyclone. Wang et al. (2011) developed a theoretical density distribution model for the cyclone by introducing turbulent diffusion into calculations of centrifugal settling. Their simulation results have been used in the design of a cylindrical cyclone that has exhibited effective separation and good wear resistant performance.

2.5. Problems of Traditional HM Cyclone Technology

With the traditional heavy medium coal cleaning process the feed to the heavy medium cyclone is generally deslimed at 28 mesh (0.6 mm), which is dictated by the smallest practical size which can be rinsed properly on a drain and rinse vibrating screen. This requires a large amount of water and a large screen area, depending on the percentage of -28 mesh in the raw coal feed. Past practices also have generally dictated that the -28 mesh raw coal should be cleaned in separate equipment, such as froth flotation, water only cyclones, Deister tables, spirals, TBS or combinations of them. However, each of these units has some disadvantages. For example, oxidized coal cannot be treated in froth flotation without excessive loss of Btu's in the tailings. Each of these pieces of equipment may have limitations insofar as the top or bottom size of the coal to be treated. This limitation results in loss of coarse product to the tailings in the froth flotation or the finer sizes may not be cleaned at all in some processes. There is also a limitation of the lowest practical specific gravity of separation. Mechanical cleaning of the -28 mesh product below a gravity of 1.5 s.g. is rarely accomplished with any degree of efficiency. This, coupled with a very substantial decrease in the sharpness of separation (often measured by Ep value. Smaller Ep value represents more accurate or sharper separation) as the grain size decreases and a very large difference in the specific gravity of separation between the coarse and finer sizes of the -28 mesh fraction, results in an overall loss in efficiency which cannot be economically justified.

2.6. Advantages of HM Cyclone Cleaning of Coal to Zero

There are several reasons why the cleaning of coal to zero in heavy medium cyclones is very attractive. Among these is the ever increasing amount of -28 mesh as a result of mechanized mining, conveying, and storage. The increase in fines almost always has a high proportion of near gravity material (Mengelers and Absil, 1976; Vanangamudi and Rao, 1987), which demands as sharp a separation as is practical.

Heavy medium cyclone cleaning of the -28 mesh material has a very low Ep value. It may range from 0.03 to 0.08, depending on the specific gravity of separation and the size composition of the raw coal feed. This, coupled with the small differences in the gravity of separation between the grain size fractions that are encountered in -28 mesh material, makes the heavy medium cyclone cleaning especially attractive.

The first attempt to clean coal to zero in heavy medium cyclones was made in 1950's by Stamicarbon DSM in Europe (Krijgsman, 1952; Matsuno, 1960). It was discovered at that time that a large diameter cyclone with a relatively low feed pressure, which is satisfactory for the + 28 mesh product, is not satisfactory for the -28 mesh separation, since the sharpness of separation drops off appreciably in the larger cyclone. To obtain a sharper separation for the -28 mesh material in a heavy medium cyclone, the Fuel Research Institute in 1976 erected a dense-medium cyclone pilot plant for the beneficiation of minus 0.5 mm coal, and commissioned it during the first quarter of 1977. (Mengelers, J. and Absil, J. H., 1976). Fairly coarse magnetite was used in the beginning. Although the separations were promising, fairly high losses of magnetite (about 2 to 3 kg per ton of feed coal) were recorded. These losses relate to magnetite that adhered to the products, and exclude any losses in the effluent, which were not measured. In an attempt to improve the separating performance, much finer magnetite was employed. The plant efficiency improved dramatically, but, as the very fine magnetite was gradually lost from the circuit, the separations deteriorated.

They also found that they must increase the centrifugal forces acting on the coal in the heavy medium cyclones to produce a sharp separation in particles down to 200 mesh range. This can be accomplished by applying a smaller diameter cyclone or increasing the feed pressure to cyclone. Reducing the overall range of size into the cyclone also has some distinct advantage. Thus using a separate cyclone for the -28 mesh cleaning is very helpful and may be necessary.

When the heavy medium cyclone is used to clean coal to zero it is extremely important to carefully calculate and control the heavy medium withdrawn from the heavy medium tank containing -20 mesh or -0.85 mm product to keep the circuits in equilibrium and prevent build-up of -20 mesh coal in the heavy medium circuit (Vanangamudi and Rao, 1987). It has been proven (Mengelers and Absil, 1976; Vanangamudi and Rao, 1987) that this balance can be maintained in a circuit, and the percentage of solids, including impurities, in the heavy medium circuit can be kept at a level to obtain good separation.

Dense-medium processing of fine coal is still the most efficient method of fine coal cleaning available. It has been successfully implemented at several plants around the world in the past and is presently in use in South Africa and China. Provided that the appropriate combination of cyclone geometry, magnetite medium and cyclone feed pressure is applied, very good separation efficiency and accurate control over final product quality can be obtained when processing fine coal in dense-medium cyclones.

2.7. Innovative GTC Non-deslimed Non-classified Gravity-fed Heavy Medium Cyclone

The proposed program is aimed at developing, demonstrating and evaluating the innovative GTC non-deslimed non-classified gravity-fed heavy medium cyclone as applied to Kentucky coals to considerably improve coal cleaning efficiency and reduce costs. Guohua Technology Corporation or GTC is an American subsidiary in Lexington, Kentucky owned by a Chinese company, Beijing Guohua Technology Group (BGTG). BGTG is a technology and engineering company specializing in coal preparation with more than five hundred employees of which more than three hundred are design and process engineers. It is a dominant player in the business of coal preparation plant design and construction in China and beyond. In fact, it has designed and built almost five hundred coal preparation plants based on their non-deslimed heavy medium cyclone technology since 2000. The GTC heavy medium cyclone has several unique features and offers distinctive technical advantages described below:

2.7.1. Unique design

As schematically illustrated in Figure 2.1, the GTC non-deslimed gravity-fed 3-product H.M. cyclone consists of the first-stage cylindrical unit and the second-stage cylindroconical unit which are connected in series. Only the medium suspension enters tangentially the first-stage cyclone under certain pressure while raw coal goes into the cyclone axially at the top end by gravity. The rotating medium creates an open vortex throughout the length of the cylinder. A rotational motion is quickly imparted upon particles by the open vortex. Under the effect of centrifugal force the light material (coal) moves toward the air core and are then discharged along with the central air core through the overflow tube at the bottom without coming into contact with cyclone wall. The heavy (and generally abrasive) material is swung out

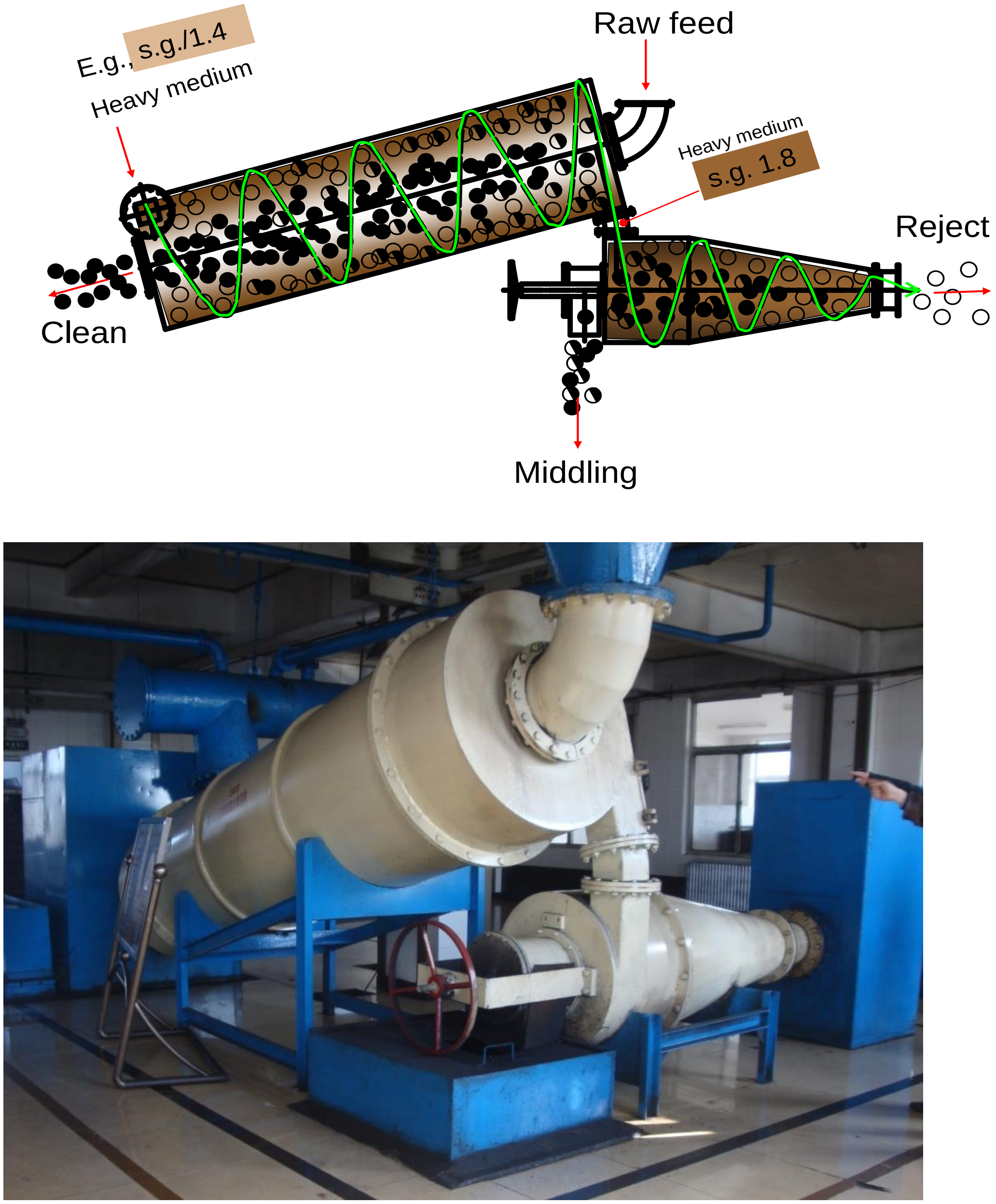

Figure 2.1. Schematic illustration (top) and picture (bottom) of the gravity-fed 3-product H.M. cyclone.

almost immediately and leaves the cylinder via the upper tangential sink outlet and enters the second-stage cyclone under the influence of the axial velocity of the outer spiral flow. Only near gravity particles of coal which are separated further along the unit axis actually come into contact with the cyclone body, minimizing wear of the unit. The medium suspension that goes into the second-stage cyclone is subjected to thickening and size classification under the influence of centrifugal force in the cylinder and thus contains higher magnetite concentration than the original heavy medium and also has coarser magnetite particles. This creates a favorable density separation condition for the heavy materials that move from the cylindrical cyclone into the cylindroconical cyclone which is essentially a Dutch State Mine (DSM) cyclone discussed earlier.

2.7.2. Structural features

Compared to other cylindrical cyclone such as DWP cyclone, GTC heavy medium cyclones have several structural features:

1) There is no vortex finder for the clean coal discharge, which was found to increase the particle retention time in the cyclone, reduce contamination of refuse to clean coal and improve separation precision.
2) The geometry (e.g., length/diameter ratio) of the cyclone is optimized for best separation performance. In addition, the GTC cyclone operates at a moderately higher heavy medium pressure than conventional H.M. cyclones, which is known to improve separation efficiency, especially for finer coal particles (Ferrara, 1995; Abbot et al., 1996; Majumder et al., 2006).

3) There are three product outlets, making it possible for the cyclone to produce three products, *i.e.* clean coal, middlings and refuse simultaneously by use of a single low-density medium suspension. This provides a favorable condition for facilitating process simplification and equipment layout.

4) The first stage cyclone is in a cylindrical form in which the dense medium suspension has a uniform density field and reacts slowly to the change of suspension density. This is beneficial to the enhancement of separating precision. The second stage cyclone consists of a cylindroconical unit. This is conducive to the production of low ash clean coal in the first stage and true refuse product in the second stage due to the larger difference between the actual separating densities of these two stages.

5) Owing to the facts that the raw coal and dense-medium suspension are separately fed into cyclone and the raw coal goes into cyclone by gravity through the feed tube arranged centrally at the top of the cyclone, a number of advantages can be expected:

    i. Only the heavy materials move radially outward across the “separating cone” whereas in a conventional cyclone to which coal is fed under pressure together with the medium, both heavy and light materials move radially across the “separating cone”, causing mutual interference. This will lead to lower loss of clean coal and higher separating precision.

    ii. Since the raw coal feed enters the cyclone by gravity, the power consumption for coal slurry pumping is eliminated.

iii. With the elimination of pumping operation, the generation of secondary slimes is minimized, which helps downstream operations such as filtering, thickening, and waste water disposal.

iv. Without the restriction imposed by the coal slurry pump, the upper size limit of coal feed can be extended.

v. The process flowsheet is simplified and less equipment is needed, saving the capital and operating costs by 20-30%.

vi. An accurate measurement of the density of medium suspension can be readily performed, without the complications caused by changes in raw coal properties. This is beneficial to the implementation of automatic density measurement and control.

6) On-line adjustment of the practical separation density of the second stage cyclone can be made by varying the size of the underflow orifice and the insertion depth of the vortex finder of this stage. With the use of an external vortex finder insertion depth adjustment device to replace the internally configured mechanism, the separation density of the second stage can be made in a more convenient and flexible manner.

7) There are no moving parts and the cyclone is lined with corundum material with a Vickers micro-hardness of HV = 835.8. The cylindrical body has a service life of over 9000 hours or 2 years under normal working conditions.

2.7.3. Operating Performance

The separation performance of the GTC heavy medium cyclone can be described as follows:

1) GTC cyclone offers high separation precision. Typical separation performance parameters of GTC heavy medium cyclones are shown in Table 2.1. The 2NZX cyclone is a conventional pressure-fed medium-sized H.M. cyclone with a diameter of 600 mm or 0.6 m and the 3GDMC cyclone is a large-sized GTC three product heavy medium cyclone. The specification for the GTC cyclone is designated by the diameters of the first- and second-stage cyclone. For example, 3GDMC 1400/1000 indicates that the first stage cylindrical cyclone has a diameter of 1400 mm or 1.4 m (approximately 4.5 ft.) and the second stage cylindroconical cyclone has a diameter of 1000 mm or 1.0 m (approximately 3'4"). By comparison, the GTC heavy medium cyclone, even though its diameter is considerably greater than the conventional H.M. cyclone, offer a much better separation precision measured by the Ep value.
2) GTC cyclone is capable of producing clean coal, middlings and refuse products simultaneously by using a single low-density medium suspension, simplifying the flowsheet and eliminating a group of equipment that is needed for high-density suspension preparation, circulation and recovery if a second stage of conventional H.M. cyclone is employed to produce the middlings or high ash clean coal.

3) GTC cyclone can be used to carry out high-density separation with a low-density medium suspension since the thickened heavy medium enters the second stage cyclone from the first stage cyclone, as discussed above. This leads to simplification of the process flowsheet, reduction of wear of equipment and pipes, and lower heavy medium and power consumption.

Table 2.1. Separation Performance of Different H.M. Cyclones

Cyclone	2NZX	3GDMC	3GDMC	3GDMC
Feeding mode	Pumping	By gravity		
No. of products	2	3		
Specification	Φ600(1st-stge)	1400/1000	1300/920	1200/850
Feed size, mm	30~0	100~0	80~0	60~0
Separation density (1st-stage), $\delta_1/\text{kg}\cdot\text{L}^{-1}$	1.450	1.430	1.410~1.450	1.485~1.500
Ep (1st-stage) E_1, $\text{kg}\cdot\text{L}^{-1}$	0.035	0.025~0.034	0.019~0.027	0.025~0.040
Separation density (2nd-stage), $\delta_2/\text{kg}\cdot\text{L}^{-1}$	1.750	1.683	1.680~1.850	1.871~1.901
Ep (2nd-stage), $E_2/\text{kg}\cdot\text{L}^{-1}$	0.062	0.050~0.065	0.035~0.043	0.036
Organic efficiency, %	>90	99.00	95.20	95.76
Capacity, t/h	50~70	500~550	350~450	250~350

4) GTC cyclone is able to handle a raw coal feed with an upper size limit of 100 mm (4”) with an effective lower size limit of separation of 0.25 mm vs. approximately 1 mm for other cyclones. The lower size limit of separation of GTC cyclone can be reduced to 0.075 mm or 200 mesh, as shown in Figure 2.2 (Zhao and Yu, 2012), when it operates together with a smaller diameter cyclone in a proprietary GTC fine coal heavy-medium cyclone cleaning circuit shown in Figure 2.3, which eliminates the need for low efficiency

gravity separators for fine particles such as TBS or spiral (Sebastiao et al., 2009). Essentials of the proprietary GTC cyclone cleaning process are described as follows: Under the cyclone's classification and thickening effects, the medium suspension discharged from the first stage cyclone along with the light material usually contains finer solids (magnetite and coal) and has a lower density. A portion of the split flow of this suspension is diverted into a fine coal H.M. cyclone with a smaller diameter for separation of coarse slime. As a result, the quantity of coal fines to the costly flotation circuit is drastically reduced and the ultra-fine medium suspension preparation and circulation system often needed for ultrafine coal H.M. separation is eliminated. Figure 2.2 clearly show that the GTC heavy medium cyclone can clean fine coal more efficiently than TBS or spiral.

5) GTC cyclone is capable of treating unsized and non-deslimed raw coal feed. It is currently a common practice to have the cyclone treat sized and deslimed raw coal, e.g., 3/8 or ¼ in. - 0.5 mm. This practice is based on the assumptions: i) desliming is the only way to enhance the separating precision and reduce the difficulty in medium draining operations, and ii) only by means of treating the coarse, intermediate and fine coal separately, can the yield of overall clean coal be sufficiently high. However, the technical advantages of cleaning coal to zero in heavy medium cyclones has been documented before (Mengelers and Absil, 1976; Vanangamudi and Rao, 1987) and the recent practices at almost five hundred coal preparation plants in China and other countries since year 2000 (Zhao et al., 2010; Zhao

and Yu, 2012) have proven that the use of GTC gravity-fed 3-product H.M. cyclone to treat unsized and non-deslimed coal is technically feasible and commercially successful and offers enormous technical and economic advantages over the traditional heavy medium separation process.

2.7.4. Heavy Medium Consumption by Non-deslimed Cyclone

The heavy medium consumption by the GTC H.M. cyclone without desliming and sizing is the major concern for coal preparation professionals and coal companies. Industrial applications at almost five hundred coal preparation plants have shown that the average heavy medium consumption is approximately 0.5 kg/t or 1 lb/t for Chinese coals which are finer and more difficult to clean than the U.S. coal. Competitive heavy medium consumption by GTC non-deslimed cyclones is achieved because:

1) GTC cyclones use a lower S.G. magnetic suspension, e.g., 1.4, to achieve a separation at S.G., e.g., 1.8 or even 2.1, as discussed above, whereas the conventional HM cyclone must use a high density suspension. For a magnetite suspension of 1.4 S.G., a magnetite concentration of 35.54% by wt or 9.76% by volume is needed. In contrast, a 1.8 S.G. magnetite suspension requires a magnetite concentration of 55.28% by wt or 19.51% by volume. Lower concentration of magnetite tends to result in a smaller loss.

2) GTC cyclones reduce secondary fines by 5-7 absolute percentage points as a result of gravity feeding rather than pumping. Reduced amount of fines makes magnetic recovery of heavy medium more efficient.

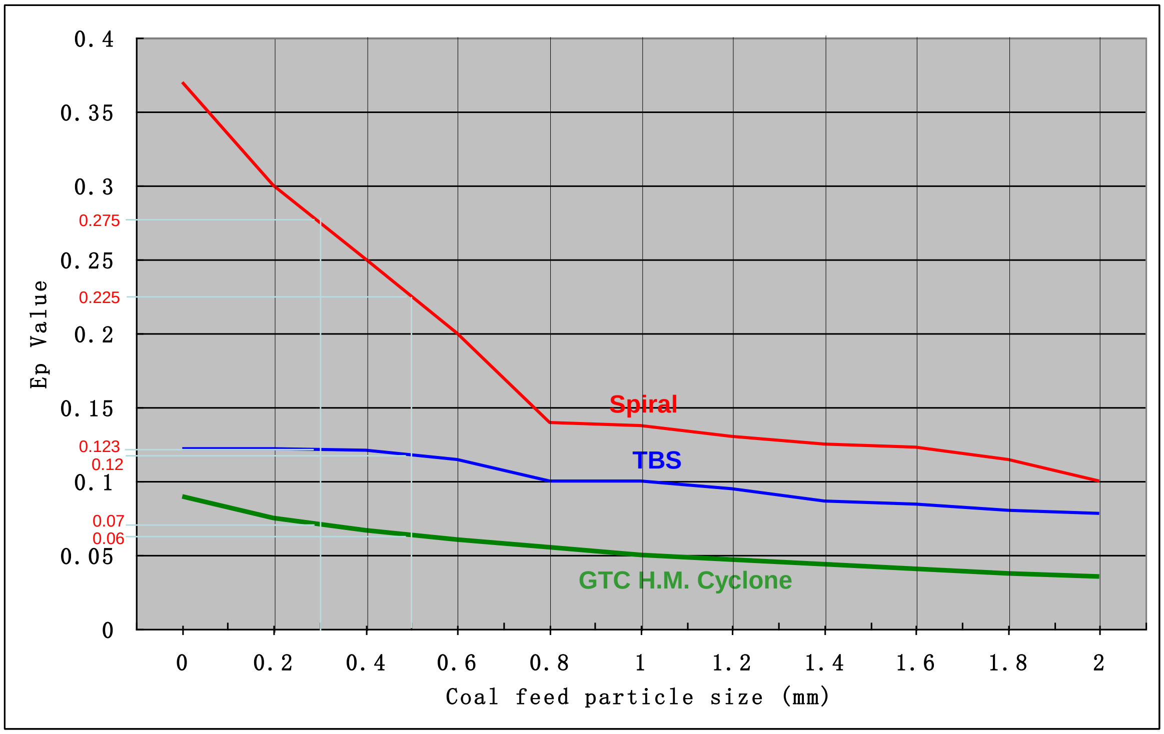

Figure 2.2. Ep values for different coal particle sizes with three separation devices.

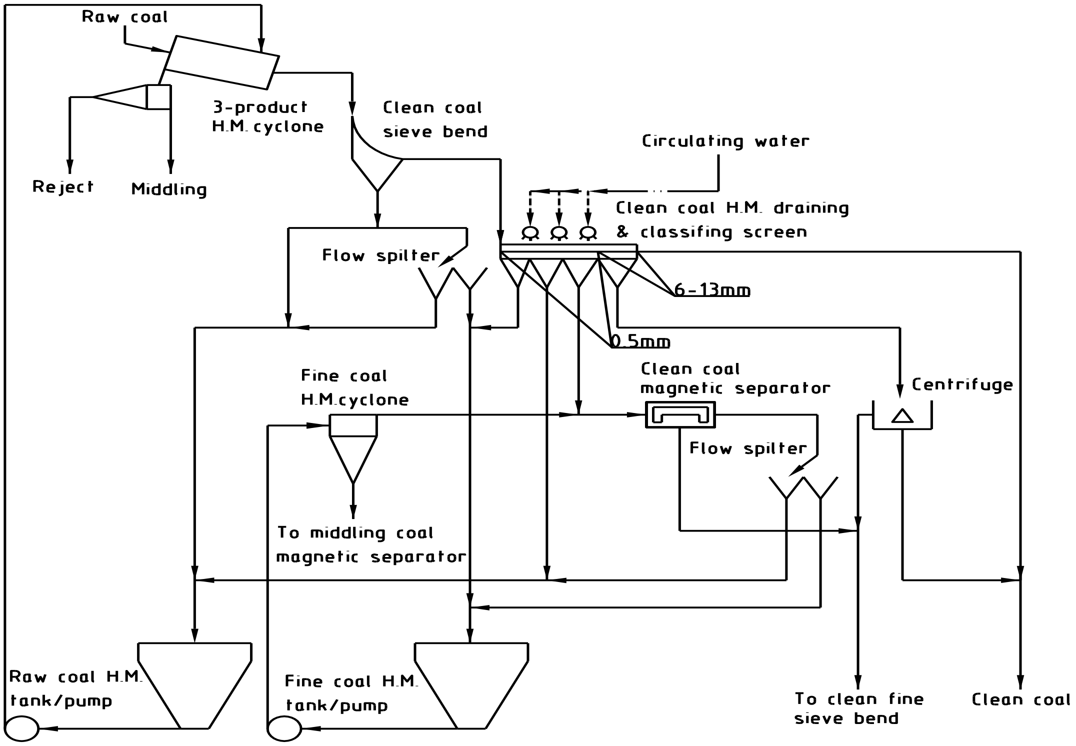

Figure 2.3. Proprietary GTC HM process flowsheet with fine coal H.M. cyclone

3) Higher operating pressure of heavy medium increases medium velocity inside the cyclone which reduces viscosity, improving separation efficiency of both cyclone and magnetic separator.

4) Fine magnetite primarily goes to the coal product while coarse magnetite mostly reports to the tailings high in clays. Different magnetic separators are used to recover magnetite from clean coal and tailings, which makes magnetite recovery much more efficient. Most of magnetite loss is associated with fine magnetite in the tailing high in clay because fine magnetite particles are very difficult to separate from clay particles.

5) Special caution is paid to ensure that a sufficient amount of circulated H.M. suspension is split out to avoid too high a viscosity of the heavy medium, which is critical for stable operation of the system.

6) Magnetic separators are properly selected and a sufficient number of magnetic separators are employed.

3. CHAPTER 3 – EXPERIMENTAL

3.1. System Installation and Shakedown

The GTC demonstration and testing circuit for this research was constructed in the coal and minerals processing laboratory located in the Mining and Minerals Resources Building on the University of Kentucky main campus. As shown in Figure 3.1, the pilot-scale system consisted primarily of a 200 mm (8-inch) diameter GTC cyclone, a dense medium pump, a framework, sumps, mixers, pipes, and auxiliary components. The circuit had the capability of providing 160 to 180 gallons per minute of medium volumetric flow to the DM cyclone resulting in a mass throughput capacity ranging from 8 to 12tph depending on the medium-to-coal (M:C) ratio, which is calculated on a volumetric basis.

A pressure gauge located in the feed pipe near the cyclone inlet was used to ensure proper pressure. Feed pressure requirements were based on static head expressed in feet and as a function of the number of cyclone diameters. For example, the DSM standard is 9 times cyclone diameter (*i.e.*, 9 × 8-inch diameter ÷ 12 inches per foot) or 6 feet, which converted to gauge pressure indicates the need for 2.7 pounds per square inch (psi).

Issues such as converting fittings from metric to empirical, leakage at connecting joints, and pressure gauge calibration were solved. After successfully installing the system, exploratory no-load testing of the system was performed with only heavy medium to examine system functionality and dependability before coal was fed to the system.

Figure 3.1. GTC three-product DMC circuit with 200-mm (8-inch) cyclone, feed, sump, and pump.

3.2. Test Procedure

General experimental procedures involved the following sequential steps:

- Medium preparation: Calculate magnetite and water amounts needed for different medium density levels. Prepare medium in a barrel, then pump into the sump to avoid plugging the sump with magnetite.

- Medium density calibration: Samples collected from the recycling feed stream are measured with a Marcy's scale. More magnetite or water is added to the sump if the specific gravity is lower or higher than the desire value.

- Pressure control: Desired feed pressure is achieved by adjusting pump voltage.

- Coal addition: Calculate amount of coal needed based on target M:C ratio. Slowly add feed coal into sump containing heavy medium.

- Samples collection: After operating the circuit for approximately 10 minutes at desired conditions, collect samples from each stream (recycling feed, clean coal, middlings, tailings) using a specially designed slurry sampler.

- Assay measurements: Screen to remove magnetite, dewater, dry, and grind samples to prepare for ash, total sulfur, and calorific analyses.

- Response calculation: Calibrate assays based on referable yield acquired from tracer tests and calculate responses such as recovery and separation efficiency.

One of the most difficult challenges in the research was determination of mass yield to each stream. Large flow rates prohibited accurate direct measurements using a stopwatch and a calibrated container. The next option was to utilize the three-product equation to determine the product mass yield (Y_p), *i.e.*

$$\mathrm{Y_P} = \frac{\mathrm{b_f(a_2 - a_3) + b_2(a_3 - a_f) + b_3(a_f - a_2)}}{\mathrm{b_1(a_2 - a_3) + b_2(a_3 - a_1) + b_3(a_1 - a_2)}} \tag{1}$$

where a_f , a_1, a_2, and a_3 are ash contents of feed, clean coal product, middlings, and tailing streams, respectively; and b_f , b_1, b_2, and b_3 are another assay of the same respective streams. Calorific value was used for this other assay, but its dependency on ash content makes the parameter inadequate for the balancing effort. Total sulfur value differences and their relative accuracy make the calculation very sensitive.

Due to the difficulty in obtaining an acceptable result using these two methods, tracer blocks were used to model feed washability characteristics and assess yield directly by collecting blocks after passing through the unit and physically counting the number of blocks in each density fraction reporting to each process stream. The mass yield value obtained using tracers was used as a starting point along with sample analytical data to determine the mass yield resulting from each test condition.

3.3. Magnetite & Medium Stability

Magnetite used in this study was standard Grade B obtained from Quality Magnetite. Approximately 4500 pounds of magnetite were used throughout the study to prepare the heavy medium suspension at desired density values. Approximately 90% of the magnetite was finer than 45 microns (325 mesh).

To prepare the medium, approximately 150 gallons of water was added to the feed sump. Based on the desire medium density, a required amount of magnetite was weighed and added to the sump while a mixer and recirculation pump was operating.

A concern with the operation of the cyclone was medium stability under all test conditions to be investigated, particularly at low medium density values (*i.e.*, 1.4 RD) and high feed pressures (*i.e.*, 15 × cyclone diameter). Therefore, a stability study was conducted under all conditions by operating the circuit with medium only (*i.e.*, no coal) while collecting samples and measuring medium density in the overflow and underflow. An industrially acceptable difference in overflow and underflow density values is 0.4. Medium stability test results are provided in Figure 3.2.

The only condition that did not meet the industrial standard was with feed pressure at the highest level and medium density at 1.35 RD. Stability at a feed pressure equivalent to 12 cyclone diameters was marginally acceptable. Based on these results, a minimum RD of 1.4 was selected for the investigation while feed pressures as a high as 15 cyclone diameters were considered acceptable.

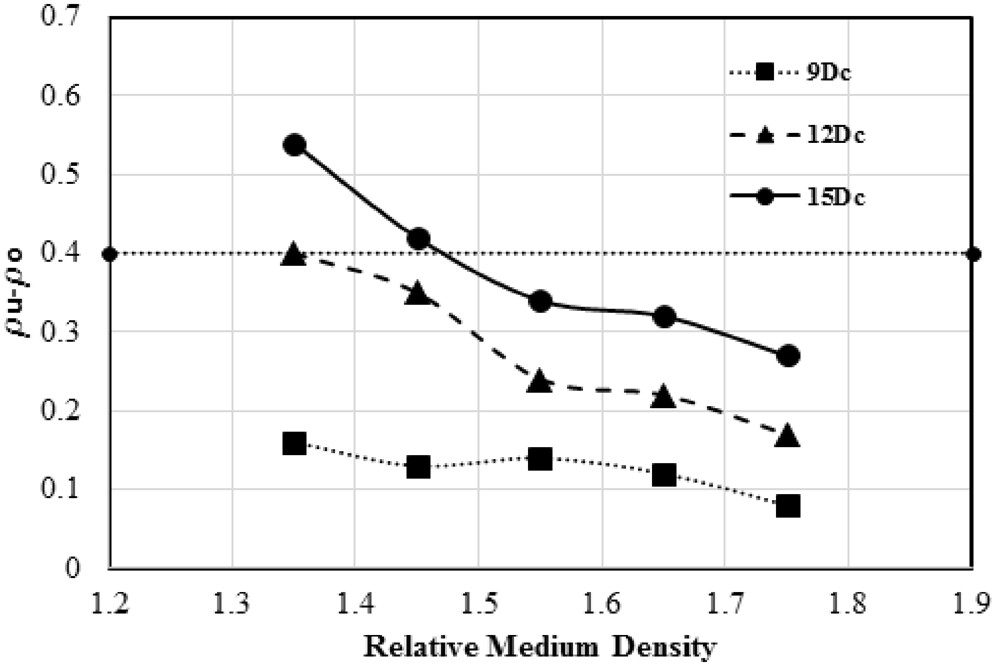

Figure 3.2. Medium stability in the GTC dense medium cyclone as a function of feed pressure expressed as static head and in terms of the number of cyclone diameters.

3.4. Feed Washability Analysis

Around 1.5 tons of nominal 6 × 1 mm (1/4 inch × 16 mesh) coal were collected and transported from Peabody Energy's Willow Lake coal preparation plant, which treats primarily Illinois No. 6 coal. Several drums of minus 1 mm (-16 mesh) were also obtained to allow an investigation into the ability to treat 1 × 0.15 mm (16 × 100 mesh) coal in the GTC three-product DMC unit and to measure the effect of slimes on separation performance. All feed samples were dewatered and dried to allow accurate calculation of the M:C ratio for each test. All coal samples were thoroughly mixed after drying to reduce feed variability from test to test.

The 6 × 1 mm coal sample was collected from the deslime coal screen overs. This material is currently treated using standard DMCs. A representative sample was subjected to washability analysis using lithium metatungstate (LMT) as the medium. Washability data, provided in Table 3.1, show that ash, total sulfur, and calorific content of the feed coal were 28.20%, 2.85%, and 12556 Btu/lb., respectively. This data indicates that a fairly easy density-based separation performance is achievable for separation RD values above 1.50. A gravity cut-point (ρ_{50}) of 1.60 would provide ash and total sulfur content of 9.28% and 2.71%, respectively, in the float product while recovering 72.1% of total weight. Tailings ash content would be 77.09%. The amount of near gravity material is a very low at 2.97%. However, significant sulfur reduction requires lowering ρ_{50} to below 1.4, which would be detrimental to mass recovery. Interestingly, more material exists in the 1.3 × 1.4 gravity fraction than the 1.3 float fraction, which makes separation difficult below a ρ_{50} of 1.50.

Table 3.1. Washability data for 6 × 1 mm Illinois No. 6 coal used in study.

Specific Gravity		Incremental				Cumulative Float		Cumulative Sink	
Sink	Float	Weight (%)	Ash (%)	Sulfur (%)	Btu/lb.	Weight (%)	Ash (%)	Weight (%)	Ash (%)
	1.3	22.25	4.74	2.29	13956	22.25	4.74	100.00	28.20
1.3	1.4	42.48	9.14	2.66	13183	64.73	7.62	77.75	34.91
1.4	1.5	5.95	21.28	4.00	11381	70.68	8.77	35.27	65.96
1.5	1.6	1.42	34.43	5.33	9846	72.10	9.28	29.32	75.02
1.6	1.7	1.55	40.86	4.68	8935	73.65	9.94	27.90	77.09
1.7	1.8	1.22	44.79	6.56	7781	74.87	10.51	26.35	79.22
1.8	2.1	4.60	61.20	3.39	4846	79.47	13.44	25.13	80.89
2.1		20.53	85.31	3.26	662	100.00	28.20	20.53	85.31

3.5. Parametric Study

A 3-level Box-Behnken design test program was developed using a software Design-Expert 5.09® acquired from Stat-Ease Inc., Minneapolis, MN to obtain results that will lead to an improved understanding of the parameter value impacts on separation performance. The parameters and their respective ranges are provided in the Table 3.2. The M:C ratio is determined on a volumetric basis. To determine the coal volume required, the average solids density was determined using the data in Table 3.1.

Table 3.2. Parameters and their ranges in the three-level statistically designed evaluation.

Parameter	Test Level		
	-1	0	+1
Medium Density	1.4	1.5	1.6
Feed Pressure	$9*D_c$	$12*D_c$	$15*D_c$
Medium:Coal Ratio	3:1	4:1	5:1

Table 3.3. Randomized test conditions investigated in the three-level experimental design.

Test No.	Feed Pressure (psi)	Relative Medium Density	M:C Rate
1	3.33	1.4	5:1
2	4.55	1.4	4:1
3	2.13	1.4	4:1
4	3.33	1.4	3:1
5	2.28	1.5	5:1
6	4.88	1.5	5:1
7	2.28	1.5	3:1
8	4.88	1.5	3:1
9	3.80	1.6	5:1
10	2.43	1.6	4:1
11	5.20	1.6	4:1
12	3.80	1.6	3:1
13	3.57	1.5	4:1
14	3.57	1.5	4:1
15	3.57	1.5	4:1

A three-level experimental design involving three parameters requires a total of 15 tests. The design program randomized the order of test conditions, as shown in Table 3.3, to minimize any impacts associated with conducting experiments in an ordered fashion. Feed pressure values were converted from static head (in feet) to gauge pressure (in psi), which results in varying levels of pressure values due to changes in medium density. In other words, the amount of pressure exerted on a given area is a function of the density of the material resting on the given area. As a result, static head values were maintained at the three levels listed in Table 3.2.

3.6. Tracer Tests

As previously mentioned, tracer blocks were utilized to provide an initial assessment of mass yield to each product stream and to evaluate performance under the prescribed test conditions. A total of 400 tracer blocks having relative densities between 1.3 and 2.0 were utilized in the study. There were 50 blocks having a relative density of 1.3, another 50 at 1.4, and so on for each density in increments of 0.1 up to 2.0. When the goal was an initial assessment of mass yield, feed coal was simulated as shown in Figure 3.3 using one density block to represent one volumetric percentage point in each density fraction. For separation efficiency determinations, all 400 tracers were added into the gravity-feed port of the cylindrical cyclone.

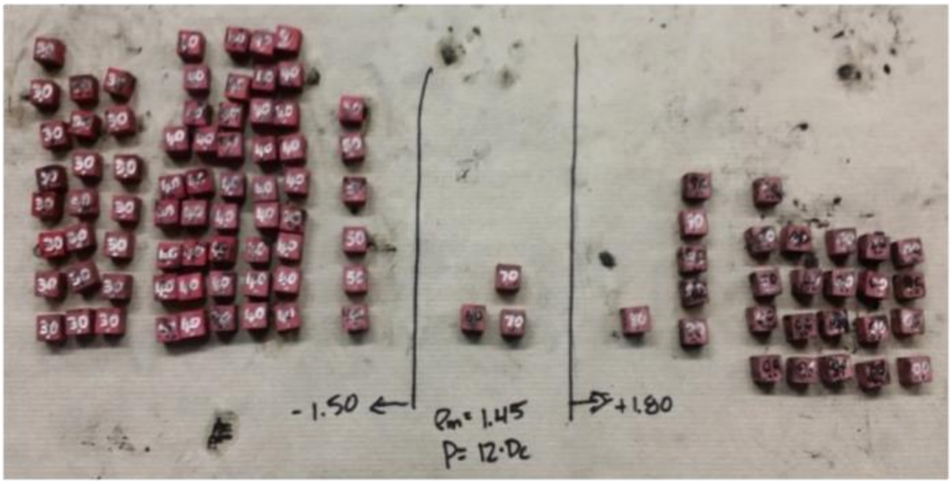

Figure 3.3. Tracer blocks simulating feed washability that were used to achieve an initial assessment of mass yield.

Tracers were gravity fed directly into the three-product DMC through the feed port located near the top of the unit as shown in Figure 3.4(left). Figure 3.4(right) shows screens mounted in buckets and positioned under the discharge of each process stream to collect tracers. Tracers collected from each process stream were arranged, again as shown in Figure 3.3, and counted to estimate a theoretical yield that was used to achieve a mass balance given assays from each parametric test.

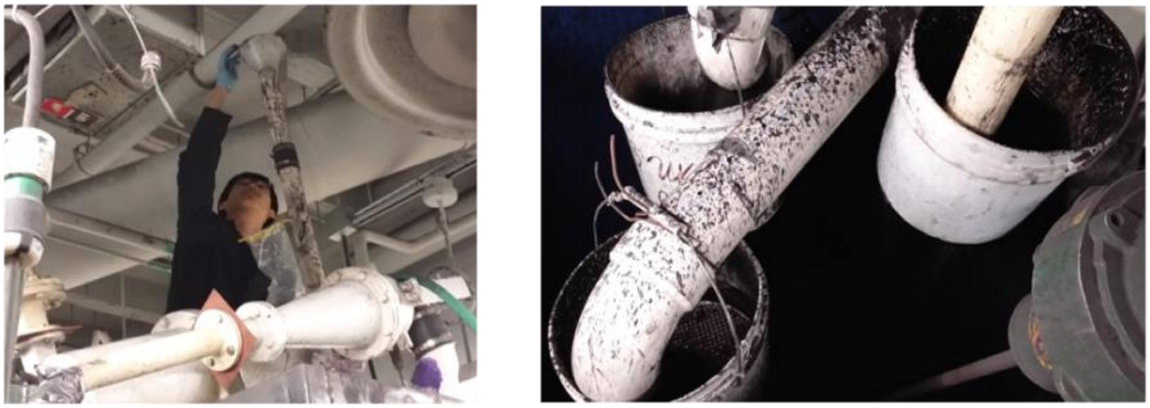

Figure 3.4. Method used to gravity feed tracer blocks into the three-product DMC(left) and collect tracer blocks from product streams (right).

3.7. System Optimization

Results obtained from the 15-test statistical design were used to develop empirical models describing response variables as a function of operating parameters and their associated interactions. The most significant parameter and parameter interactions were identified from a statistical analysis of experimental results using response surface methodology (RSM). The primary response selected for this study was separation efficiency, which is defined as the difference between combustible recovery and ash recovery to the clean coal product. The secondary response was clean coal ash. Using these empirical models, the set of operating parameter values providing the optimum separation performance were identified.

Under these optimum conditions, additional tests were conducted to evaluate the effect of adding 1 × 0.15 mm material to the cyclone feed at a concentration of 20% by weight. In addition, the impact of slimes (*i.e.*, nominally -0.15 mm material) was investigated by blending the 80:20 mixture of coarse and fines with varying amount of slime material. The three levels of slime concentration added to the cyclone feed were 0%, 10%, and 20% of total feed.

Samples collected from these tests were wet screened into various particle size fractions and the material in each size fraction larger than 0.15 mm (100 mesh) was subjected to ash, total sulfur, calorific, and washability analyses. Washability data were used to generate partition curves enabling the determination of separation density cut-point (ρ_{50}), probable error (Ep), and organic efficiency. During these tests, the entire set of 400 tracer blocks were fed with coal in an effort to generate partition curves comparable with those generated from coal washability data.

4. CHAPTER 4 – RESULTS AND DISCUSSIONS

4.1. Parametric Study

Separation performance data for all 15 tests involved in the parametric study are provided in Tables 4.1 through 4.3. Average feed ash and total sulfur content were 27.98% and 3.87%, respectively. Feed ash content varied over a range from 25.83% to 32.11% with a standard deviation of 1.85%, which indicates that ash content in the majority of tests was near the mean value. Variation in total sulfur content was more significant with a range from 2.93% to 4.75% and a standard deviation of 0.66%. A problem source causing feed quality variances could be untimed sampling over the number of tests used for each feed batch. One batch each of heavy medium and fresh feed coal were used to conduct an average of four tests. Due to high-volume flow rates in each stream, accurately timed samples were not possible to collect. As a result, a disproportionate amount of tailings material could have been collected, which would reduce ash and total sulfur content in the feed for the next test. This impact would be greater for total sulfur content. Although the feed ash variance was relatively small, which directly impacts mass yield values, combustible recovery and ash recovery were identified as the primary separation performance assessment criteria, which normalizes performance data from test-to-test.

Table 4.1. Separation performance achieved on the basis of ash content and mass yield.

Test Number	Ash Content (%)				Product Yield (%)
	Feed	Product	Middlings	Tailings	
1	32.11	6.96	36.92	79.42	56.0
2	30.82	5.68	23.45	80.30	50.0
3	27.23	5.85	19.06	76.01	64.2
4	26.65	6.36	16.48	73.53	55.1
5	29.66	10.05	28.15	79.61	70.2
6	29.12	8.31	38.31	79.48	68.6
7	27.10	7.14	22.92	75.37	70.0
8	28.61	7.35	30.42	81.64	66.6
9	28.71	10.42	41.74	78.33	72.2
10	27.89	9.82	25.63	78.76	72.0
11	27.46	8.84	35.71	78.98	72.3
12	25.83	7.09	23.74	78.43	71.6
13	26.31	8.47	16.16	70.58	70.3
14	26.10	6.99	13.78	72.37	70.0
15	26.16	7.15	13.97	72.20	70.0
Average	27.98	7.77	25.76	77.00	66.6

The range of parametric values tested resulted in a significant variation in separation performances as indicated by product and middlings ash contents, as shown in Table

4.1. Average ash content in the product was 7.77% while average ash content in the middlings stream was 25.76%. Average tailings ash content of 77% indicates that the average performance resulted in limited coal loss as shown by a comparison with the theoretical cumulative sink ash content values of around 79.22% at a relative density of 1.80 (Table 4.1). This is the benefit of a three-product DMC. Ash content in the product reached a minimum of 5.68%, which is near the theoretical minimum as indicated by feed washability data. Middlings ash content varied widely from a low of 13.78% to a high of 41.74%. Although not always the case, high values were generally realized when product ash content was also elevated. Complex interactions when feed pressure and medium density are low could produce a low clean coal product ash content and a high middlings ash content due to unstable medium in the primary cylindrical portion, which results in a high medium density entering the secondary unit.

Significant sulfur reduction was realized as indicated by average total sulfur content in feed and clean coal product of 3.87% and 2.83%, respectively (Table 4.2). From Table 4.2, theoretical sulfur content in 1.4 and 1.8 RD float is 2.53% and 2.81%, respectively, which implies that average sulfur reduction performance by the three-product DMC corresponds to higher density separations. The lowest total sulfur content in the clean coal product was 2.47%, which is a result of rejecting around 50% of the sulfur-based components. An impressive amount of sulfur existed in the tailings stream as indicated by an average concentration of 8.79% and a high of 11.90%. If it is assumed that all of the sulfur in the tailings material is pyritic, the total pyrite in Test No. 4 tailings would be 22.3%.

Table 4.2. Separation performance achieved on the basis of total sulfur content and mass yield. (Central point samples were not assayed for total sulfur content.)

Test Number	Total Sulfur Content (%)				Product Yield (%)
	Feed	Product	Middlings	Tailings	
1	4.43	2.70	8.10	6.75	56.0
2	3.50	2.68	4.87	7.46	50.0
3	4.70	2.68	4.08	10.70	64.2
4	3.71	2.92	4.38	11.90	55.1
5	4.21	2.52	3.63	6.78	70.2
6	3.26	2.47	4.98	7.01	68.6
7	3.27	2.61	3.53	11.00	70.0
8	2.93	2.69	5.33	9.25	66.6
9	4.67	3.17	3.97	10.10	72.2
10	4.75	3.07	4.01	7.77	72.0
11	3.75	3.84	4.60	7.98	72.3
12	3.22	2.60	4.29	8.78	71.6
Average	3.87	2.83	4.65	8.79	66.6

The recovery of combustible material averaged around 84.6% to the product stream and 6.0% to the middlings stream which equates to an overall recovery of 90.6% to process streams providing a marketable product. As shown in Table 4.3, the variance in recovery was significant in both product and middlings streams; however, the range of recovery values to the tailings stream was significantly lower, *i.e.*, 7.45% to

12.92%, which indicates that the process is resistant to coal loss over a wide range in test conditions.

Table 4.3. Separation performance achieved on the basis of combustible recovery.

Test Number	Combustible Recovery (%)		
	Product	Middlings	Tailings
1	72.41	14.66	12.92
2	65.50	23.68	10.82
3	83.06	7.30	9.64
4	70.30	19.74	9.96
5	89.79	2.20	8.01
6	87.34	3.27	9.39
7	89.17	1.02	9.81
8	86.39	6.80	6.80
9	90.73	1.31	7.96
10	90.06	2.38	7.57
11	90.86	1.65	7.49
12	89.66	2.90	7.45
13	87.31	1.27	11.41
14	88.10	1.01	10.89
15	88.02	1.01	10.97
Average	84.58	6.01	9.41

The fact that separation performance achieved by the GTC three-product DMC was near the theoretical ultimate performance is verified by the comparison shown in Figure 4.1. Nearly all test results were near the recovery versus product ash curve produced from feed washability data.

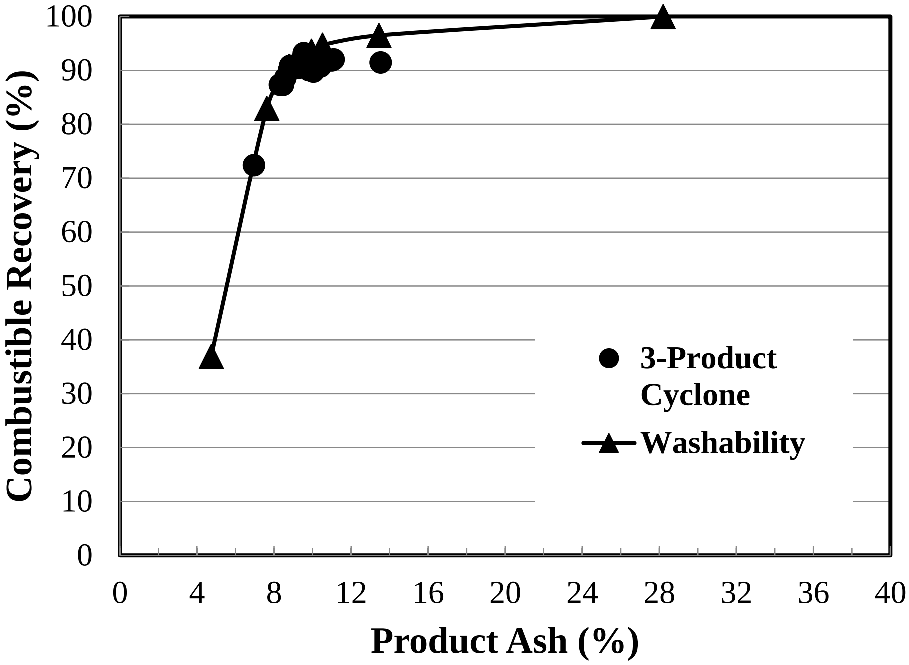

Figure 4.1. Comparison of separation performance achieved by the GTC three-product DMC with theoretical performance predicted from feed washability data.

DMC data is based on recovery and ash content to the clean coal product stream. Organic efficiency (*OE*) is considered the most meaningful criteria for monitoring process efficiency and reflects the amount of coal recovered by the process (R_A) at a given product quality compared to the theoretical maximum recovery (R_T), *i.e.*

$$OE = \frac{Actual\ Process\ Recovery}{Theoretical\ Recovery\ from\ Washability\ Data} = \frac{R_A}{R_T} * 100. \qquad [2]$$

As indicated by comparing the GTC three-product DMC performance and washability data, as shown in Figure 4.1, organic efficiency values realized from cleaning Illinois No. 6 coal using the GTC unit were in the range of 95 to 99%, which represents an exceptional performance.

4.2. Parametric Modeling & Optimization

To assist in understanding the GTC three-product DMC separation process, empirical models were developed using data from Tables 4.1-4.3. These models allow prediction of response variable values (*i.e.*, product ash content, product mass yield, and product combustible recovery) as a function of medium density, feed pressure, and feed M:C ratio and their associated interactions. These models are applicable only within those parameter value ranges provided in Table 3.2.

The three empirical models developed were statistically evaluated using an ANOVA table and were found to pass both 'model' and 'lack-of-fit' tests. Each of the model terms was tested for its significance using a hypothesis test that evaluated the probability of the corresponding coefficient having a value of zero. Model terms that passed the hypothesis test (probability greater than 10% that the coefficient is zero) were removed and the model re-tested. These resulting models with significant parameter and parameter interactions are provided in Table 4.4 along with corresponding coefficient values.

Coefficient of determination (R^2) and adjusted R^2 values for each model are also provided. They describe the fraction of separation performance results that are adequately represented by the model. The adjusted value reflects the number of terms used in the model compared to the number of parameters. An excessive number of model terms relative to the number of parameters takes away too many degrees of freedom and results in a low adjusted value. For the three models developed, R^2 and adjusted R^2 values are generally very good and indicate that these models accurately describe the performance achieved by the GTC three-product DMC.

Using these empirical models, surface response graphs, as shown in Figures 4.2 and 4.3, were created to provide a visual understanding of parametric effects. Figure 4.2 shows the well-known impact of medium density on product ash content, *i.e.*, lower medium density values provide improved product quality. The decrease in ash content with a corresponding reduction in M:C ratio was somewhat unexpected since lower M:C ratio values represent higher solids concentrations and more crowding; however, this trend may be a result of the unique characteristics of the cylindrical separation unit where overcrowding could push middlings to the second stage cyclone thereby reducing the first stage product ash content.

Figure 4.3 shows an interesting effect of feed pressure on recovery of combustible material to the product stream. As feed pressure increases from 9 cyclone diameters, recovery in the first-stage initially decreases. This is likely due to the action of centrifugal force on the fine portion of middlings particles in the feed, which accelerates their movement through the medium and into the stream reporting to the second stage; however, a recovery minimum occurs at a feed pressure equivalent to 12 cyclone diameters followed by an increase in recovery as feed pressure rises. This trend is likely due to the instability of magnetite particles comprising the medium, which allows low-density, low-ash particles to move away from the center vortex and potentially into the upward moving medium stream that reports to the second stage.

Table 4.4. Empirical models for the GTC three-product DMC describing response variables as a function of medium density (1.4-1.6 RD), feed pressure (9-15 times cyclone diameter), and M: C ratio (3:1-5:1).

Response	Model		R-Squared	Adjusted R-Squared
	Coefficient	Parameter		
Product Ash	Ash	=	0.8202	0.7712
	23.59			
	-9.26	* M:C		
	-13.15	* medium density		
	6.83	* M:C * medium density		
Yield	Yield	=	0.9053	0.8343
	3.25			
	0.01	* pressure		
	-0.04	* M:C		
	-3.49	* medium density		
	-0.002	* pressure * M:C		
	0.008	* M:C^2		
	1.21	* medium density^2		

Combustible Recovery	Recovery	=	0.9853	0.9587
	3.51			
	-0.01	* pressure		
	-0.003	* M:C		
	-3.48	* medium density		
	-0.003	* pressure * M:C		
	-0.01	* pressure * medium density		
	-0.05	* M:C * medium density		
	0.002	* pressure^2		
	0.01	* M:C^2		
	1.29	* medium density^2		

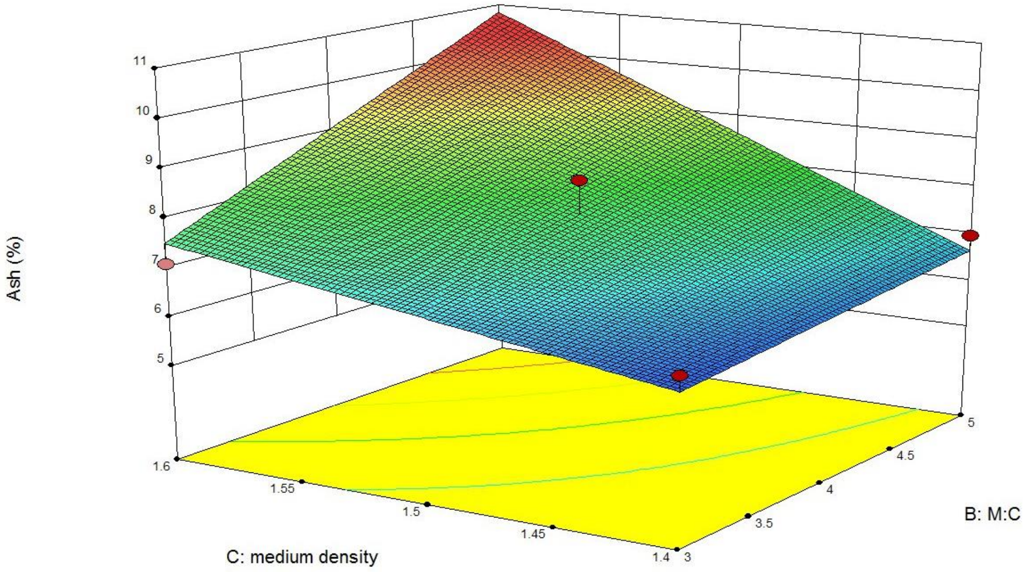

Figure 4.2. Surface response showing the impact of medium density and M:C ratio on clean coal ash content; feed pressure = 9 cyclone diameters

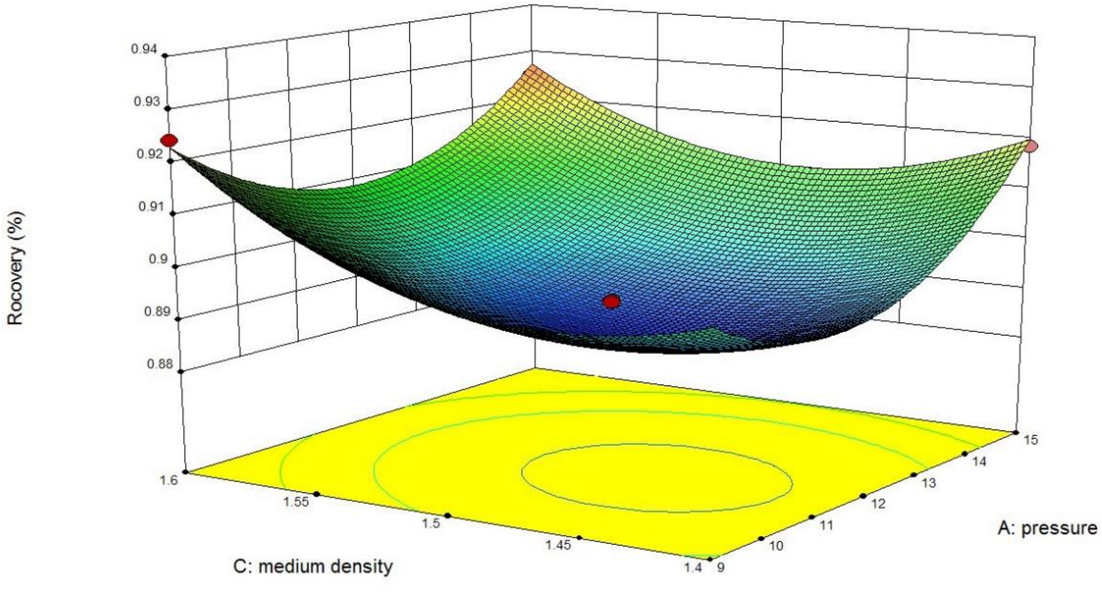

Figure 4.3. Surface response showing the impact of medium density and feed pressure on combustible recovery to the product stream; M:C ratio = 4.

4.3. System Optimization

Empirical models were evaluated using an optimization algorithm, which led to a set of conditions that maximized combustible recovery to the product stream while minimizing product ash content. Optimized parameter values were feed pressure equivalent to 12 times cyclone diameter, RD of 1.4, and M:C ratio of 3:1. These conditions were used to access the potential of increasing particle size range to a bottom particle size of 0.15 mm. The impact of slimes on separation performance was also evaluated using these optimized parameter values.

As shown in Figure 4.4, feed coal having a particle size of 1 × 0.15 mm was blended with the original 6 × 1 mm feed at a ratio of 80:20 coarse-to-fine. A single test was conducted using this blend and optimized test conditions. Collected samples were screened and analyzed to obtain separation efficiency data as a function of particle size.

To evaluate the impact of slimes on the process, nominal -0.15mm from a classifying cyclone overflow was added to the 80:20 blend at concentrations of 10 and 20% by weight. One test was conducted for each slime concentration and collected samples were again screened and analyzed to obtain separation efficiency statistics.

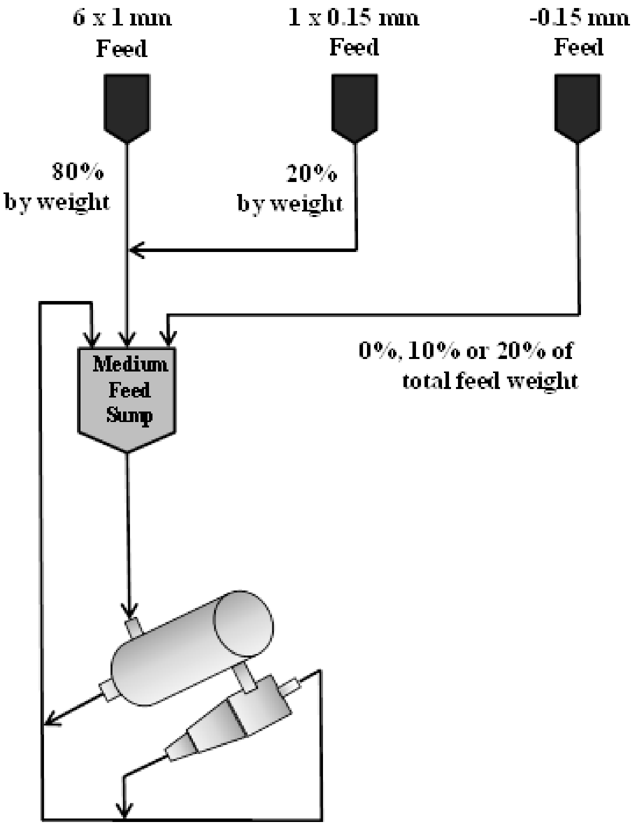

Figure 4.4. Blending of various particle size fractions
to determine the effect on separation performance.

Results obtained from these optimized tests are provided in Tables 4.5-4.7. In general, organic efficiency values were all near 100% for both 6 × 1 mm and 1 × 0.15 mm particle size fractions with and without slimes (Table 4.6). Ep values ranged from 0.03 to 0.05 for the coarser size fraction, which is slightly higher than typical values reported by industry, which reflects a slightly lower separation efficiency (Table 4.7) (Meyers *et al.*, 2013; Honaker *et al.*, 2014). Ep values achieved for the 1 × 0.15 mm fraction varied from 0.04 to 0.10, which indicates an efficiency superior to traditional technologies used by industry to treat coal in the given particle size range (Honaker *et al.*, 2013).

Table 4.5. Optimized separation performance achieved on 6 × 0.15 mm Illinois No. 6 coal on the basis of ash content at varying slime concentrations.

Size Fraction	Slime Content	Ash Content (%)			
		Feed	Product	Middlings	Tailings
6 × 1mm	0%	22.27	6.59	32.81	71.26
	10%	29.39	6.49	27.24	71.35
	20%	25.78	6.70	22.94	69.37
1 × 0.15mm	0%	33.43	8.65	17.72	78.93
	10%	27.51	5.90	13.53	74.70
	20%	34.10	5.57	12.91	74.26

Table 4.6. Optimized separation on 6 × 0.15 mm Illinois No. 6 coal on the basis of combustible recovery and organic efficiency at varying slime concentrations.

Size Fraction	Slime Content	Combustible Recovery			Organic Efficiency
		Product	Middlings	Tailings	
6 × 1mm	0	87.69	3.53	8.78	>99%
	10%	80.91	5.88	13.22	>99%
	20%	77.89	10.88	11.23	>99%
1 × 0.15 mm	0	71.84	17.67	10.50	>99%
	10%	71.10	18.34	10.56	>99%
	20%	70.07	13.53	16.40	>99%

Table 4.7. Separation efficiency data obtained from treatment of 6 × 0.15 mm Illinois No. 6 coal with and without slimes in the GTC three-product DMC.

Size Fraction	Slime Content	Ep		SG50	
		1st Stage	2nd Stage	1st Stage	2nd Stage
6 × 1mm	0	0.04	0.03	1.53	1.68
	10%	0.03	0.05	1.49	1.62
	20%	0.045	0.035	1.425	1.59
1 × 0.15mm	0	0.10	0.04	1.55	1.68
	10%	0.04	0.055	1.51	1.66
	20%	0.05	0.04	1.495	1.60

A feed RD of 1.4 produced separation gravities of 1.53 RD in the first-stage cylindrical unit for the 6 × 1 mm size fraction and 1.68 RD in the second stage (Table 4.7). A similar density cut-point was achieved for the 1 × 0.15 mm size fraction. Adding slime material at 20% concentration by weight to the feed resulted in a decrease in the effective separation density to 1.425 for the 6 × 1 mm size fraction and 1.495 for the finer fraction. The downward shift on the density cut-point is likely due to the stabilizing effect that slime material provides to the medium at low medium density values. The reduction in the density cut-point had a significant impact on combustible recovery (Table 4.6) and reduced product ash content in the 1 × 0.15 mm particle size fraction. The relative separation density difference between first and second stages was around 0.15 RD units.

A noticeable difference in performance achieved on these two particle size fractions is the ash content of middlings and tailings despite fairly similar separation density values. As shown in Table 4.5, the middlings ash content of the 1 × 0.15 mm size fraction was significantly lower while tailings ash content was higher. This is likely due to improved washability characteristics of the finer fraction.

4.4. Tracer Tests

As previously discussed, 10-mm density tracer blocks similar to that shown in Figure 4.5 were used to assist in evaluating process performance and obtaining an estimate of mass yield to each process stream. When evaluating separation performance, a total of 400 density blocks including 50 blocks in eight density fractions were fed through the gravity feed port of the GTC three-product DM cyclone. These tracers were collected from each process stream using a screen and then counted to determine the recovery of each density fraction to a given product stream.

Figure 4.5. A 1.46 SG density tracer block.

Partition curves generated in the absence of coal over a range of RD values and feed pressures are provided in Figure 4.6. A visual observation of these curves indicates that a very sharp separation was achieved under all test conditions. Feed pressure reduced the relative density cut-point in the cylindrical first-stage unit when feeding 1.4 RD medium; however, the relative density cut-point was unchanged by feed pressure for higher medium densities. In the second-stage cyclone, higher feed pressures had a greater and opposite effect in that the cut-point was increased under all medium densities tested. This finding is likely due to the concentration of magnetite in the primary unit caused by higher feed pressures, which elevated the medium density feeding the second stage.

A summary of relative separation densities from Figure 4.6 is provided in Table 4.8. The difference in cut-points between second and first stage separators was approximately 0.10 density units under low feed pressure conditions. From partition curves generated from coal washability data in Table 4.7, the difference was around 0.15 for the 6 × 1 mm size fraction. As feed pressure increased and the medium became more unstable, the cut-point differential increased from about 0.20 density units for 1.6 RD to about 0.30 density units at 1.4 RD. This knowledge is practically significant when targeting specific qualities for coal reporting to product and middlings process streams.

Tracer blocks were added to the cyclone feed in tests associated with the parametric study to determine the impact of coal on the performance predicted by tracers. Figure 4.7 compares the tracer-based performance with and without coal in the feed. In general, tracers indicate a lower density cut-point when coal was present in the feed at a M:C ratio of 4:1. For 1.4 and 1.5 RD conditions, the cut-point was about 0.1 density units lower, which is significant. Ep values remained relatively unchanged; however, the cut-point difference with and without coal was significantly lower at the higher 1.6 RD for both feed pressures. Ep increased when coal was added indicating a reduction in separation efficiency in the first stage.

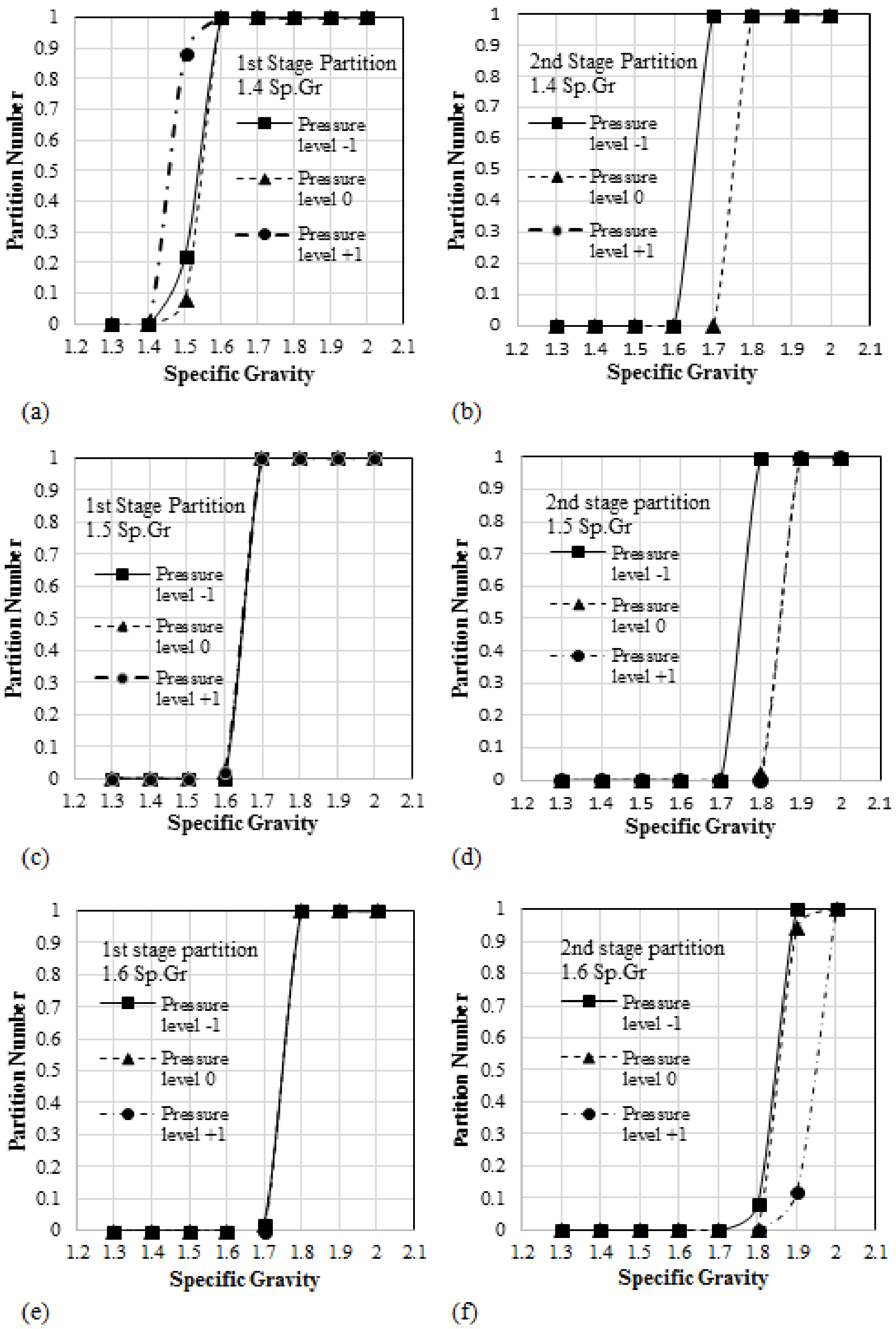

Figure 4.6. Partition curves generated using 10-mm tracer blocks at different feed pressures and RDs in the absence of coal.

Table 4.8. Summary of the relative separation density values achieved using 10-mm tracer blocks in the absence of coal in each stage of the GTC three-product DMC.

Feed Static Head (Cyclone Heads)	Relative Medium Density	Relative Density Cut-Point (ρ_{50})	
		Product-Middlings	Middlings - Tailings
9	1.4	1.535	1.65
	1.5	1.65	1.75
	1.6	1.75	1.845
12	1.4	1.545	1.75
	1.5	1.65	1.85
	1.6	1.75	1.855
15	1.4	1.455	1.75
	1.5	1.65	1.85
	1.6	1.75	1.955

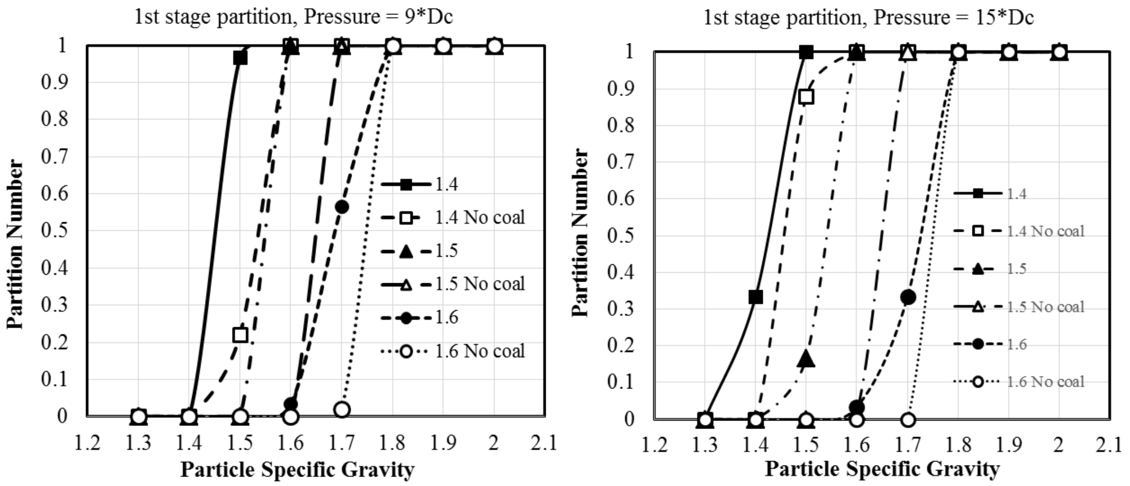

Figure 4.7. Tracer-based performance with and without coal in the first stage of the GTC cyclone at an equivalent feed pressure of 9 cyclone diameters (left) and 15 cyclone diameters (right).

5. CHAPTER 5 – CONCLUSIONS AND RECOMMENDATIONS

The GTC three-product dense medium cyclone (DMC) provides the opportunity to produce a high-quality clean coal product needed to meet contracts requiring low ash and sulfur content, a medium quality coal that can be marketed to utilities as a low-cost fuel, and a high-ash tailings material from a single processing unit. The three-product DMC is comprised of a first-stage cylindrical cyclone cleaning unit that receives the feed, produces the high-quality clean coal product, and provides feed to the secondary unit, which is designed as a conventional Dutch State Mines DMC with a cylindrical barrel and cone. Published data indicates that commercial GTC units have the ability to clean coal over a wide particle size range from as coarse as 100 mm (4 inches) to as fine as 1 mm (16 mesh) while maintaining high efficiency levels across all particle size fractions.

Essentially no separation data exists that could be used to evaluate the potential of cleaning US coals using the GTC three-product DMC. Therefore, a study was conducted to evaluate and optimize separation performance when treating Illinois Basin coal over a particle size range of 6 × 0.15 mm. A pilot-scale system was constructed for the test work. It was comprised of a 200-mm (8-inch) diameter GTC cyclone unit. The volumetric feed rate to the cyclone could be varied up to 180 gallons per minute, which provided a mass throughput capacity of around 12 tph depending on the M:C ratio in the feed.

5.1. Conclusions

A statistically designed parametric test program was conducted to evaluate parameters and quantify parameter interactions and to optimize separation performance when treating Illinois Basin coal. Using 6 × 1 mm (1/4-inch × 16 mesh) Illinois No. 6 coal obtained from Peabody Energy's Willow Lake preparation plant, a total of 15 tests were conducted while varying medium density, feed pressure, and M:C ratio. The average ash reduction was from 27.98% to 7.77% while recovering 84.6% of the material. Organic efficiency exceeded 99%. Total sulfur content decreased from 3.87% to 2.83% by rejecting around 50% of feed sulfur. Middlings material contained on average 25.76% ash and 4.65% total sulfur over the 15 tests. Approximately 6.0% of combustibles in the feed reported to the middlings stream. The high variability in ash and total sulfur content of the middlings material from test to test revealed the ability to control middlings quality by manipulation of process variables, especially feed pressure.

Performance data from the parametric study was used to develop empirical models that described combustible recovery and mass yield to the product stream as well as clean coal product ash content as a function of three operating parameters and their associated interactions. These three models were found to be statistically significant with acceptable coefficient of determination (R^2) values. Response surface plots revealed complex interactions between feed pressure and medium density for the determination of combustible recovery and product ash content. The same two parameters were also found to interact and play a significant role in controlling the difference in density cut-point achieved in the first stage cylindrical unit and the second stage cyclone.

Using the empirical models, the optimum set of parametric values needed to maximize recovery while minimizing product ash content was determined. Under optimum conditions including RD of 1.4, tests were conducted to obtain process efficiency data. The probable error (Ep) value achieved from the first stage was 0.04 while the second stage provided an Ep of 0.03 when treating 6 × 1 mm coal. The difference in first and second stage RD cut-points was 0.15 density units. As a result, about 87.7% of combustibles reported to the product stream, which contained 6.59% ash. Middlings material had an ash content of 32.81% and contained 3.53% of combustibles in the feed.

The GTC three-product DMC unit was found to be very effective for treating particles as small as 0.15mm (100 mesh) with varying levels of slimes up to 20% by weight. Coal having a particle sizes between 1 mm and 0.15 mm was blended with the 6 × 1 mm feed at a ratio of 80:20 coarse-to-fine. With no slime material in the feed, the Ep value achieved on the 1 × 0.15 mm fraction was 0.10 in the first stage and 0.04 in the second stage. Density cut-points in both first and second stages were essentially equal to those obtained for the 6 × 1 mm fraction. Another finding was a significant improvement in middlings quality compared to middlings produced from the 6 × 1 mm, which was a result of better liberation of coal and mineral matter in the finer fraction. Ep values and thus separation efficiencies are superior to the performance provided by typical processes utilized to clean 1 × 0.15 mm coal and at least equal to or better than the performance of conventional DMCs.

A number of GTC three-product DMC applications in China reportedly treat by-zero material, which simplifies the processing circuit. However, adding slime material to the feed typically has a negative impact on separation performance due to an elevation in viscosity. In the current investigation, typical slime concentrations in run-of-mine feed were studied to assess performance impact. Material from the overflow of a classifying cyclone containing particles finer than 0.15 mm was added to the 6 × 0.15 mm material at 10 and 20% concentrations by weight. The addition of slimes stabilized the medium and thus reduced the relative separation density from 1.53 RD to 1.43 RD for the 6 × 1 mm fraction and from 1.55 RD to 1.50 RD for the 1 × 0.15 mm fraction. Ep values remained relatively unchanged. As a result, the influence of the slime composition on performance is mainly to decrease the separation density offset and thus feeding by zero is achievable. The main obstacle for by-zero applications is magnetite recovery.

The evaluation of the GTC three-product DM cyclone was assisted by the use of 10-mm tracer blocks. Tracers were fed to the unit through the gravity feed port while operating the cyclone over a range of medium density values and feed pressures. The study found that the difference in the density cut-point between first- and second-stage units can be varied from 0.10 to 0.30 density units by changing feed pressure. As such, the quality of primary clean coal product can be controlled by manipulating medium density of the feed while middlings quality can be controlled by manipulating feed pressure as well as the adjustable vortex finder in the second-stage cyclone.

5.2. Recommendations

The following recommendations are based on findings obtained in and experiences gained from the current investigation:

1. The most significant issue addressed in the current study was the dynamics of the feed quality resulting from using a closed-circuit system to evaluate a relatively high throughput process unit. It is highly recommended that an in-plant test program be conducted using the pilot-scale three-product DM cyclone. An in-plant study would ensure relatively constant feed quality, which would greatly benefit a complex material balancing problem associated with a three-product unit.
2. The separation density achieved in the second stage of the three-product unit is highly dependent on operating conditions associated with the first-stage unit; however, a mechanism to adjust the vortex finder vertical position is available along with means to control the apex diameter, which may provide the ability for on-line second-stage density cut-point control. These control mechanisms need further testing and evaluation.
3. The production of a middlings stream allows for the consideration of using additional crushing of coarser fractions to improve washability characteristics and increase coal recovery to the high-quality clean coal stream. A follow-up study

is recommended to evaluate technical and economic benefits of crushing and re-processing of middlings stream material.

6. APPENDIX

6.1. Feed Acquisition and Characterization:

The feed samples had a moisture content around 15%. In order for easier calculations and implements, some initial treatments such as drying and mixing were needed to prepare the samples for further calculations and tests. The samples were initially spread on plastic sheets under room temperature then placed in the drying oven. For -28mesh samples, the slime content (-100mesh) had to be screened out first and then were subjected to the drying process. Once thoroughly dried and mixed, the moisture content was considered 0% to simplify the calculation and the feed was considered unvaried from test to test.

Figure 6.1. Raw feed samples drying process

A representative sample was taken from the feed and subjected to washability test and size analysis. The washability data was provided in the experimental section. Assays (Ash, Sulfur, Btu) were measured using analyzers manufactured by LECO.

Figure 6.2. LECO TGA701 ash analyzer

Figure 6.3. LECO AC500 calorimeter

Figure 6.4. LECO S632 sulfur analyzer

The size distribution data of the coarse feed is shown below:

Table 6.1. Feed size distribution

Size fraction	Percentage of Weight (%)		
	Test 1	Test 2	Average
-200mesh	5	4.96	4.98
100×200mesh	0.86	0.65	0.755
16×100mesh	6.6	6.86	6.73
¼”×16mesh	67.76	65.36	66.56
+1/4”	19.57	22.18	20.875

As shown table 6.1, even though coarse particles consisted a large portion of the sample, there were still around 5% of -100mesh materials existing in the coarse feed. This property will somehow impact the tests and calculations, however, it was neglected in this study.

6.2. Magnetite stability

In order to reduce the impact of medium instability or viscosity issue, it is important to be aware of the size distribution of the magnetite. By screening a representative magnetite sample at 325mesh, the amount of -44micron which generally describe the magnetite quality was known.

Table 6.2. European magnetite grade standard

European Grade	% Passing 44 micron (325mesh)
Coarse A	60
Medium B	75
Fine C	90
Superfine D	95
Ultrafine E	97

Table 6.3. Magnetite size distribution

Size fraction	Percentage of Weight (%)
-325mesh	90.24
+325mesh	9.76

Based on the European grade standard shown in Table 6.2, the magnetite used in this study was qualified for Fine C grade. To better understand how the medium stability changed with the medium density, medium with different medium densities were made and thoroughly mixed in separate beakers (2L for each). After settling for 30 seconds, half of medium was pumped out at 1L height. The left medium was screened and dried thus the amount of magnetite suspended was measured (Figure 6.5). With the increase of medium density, the amount of suspended magnetite increased significantly.

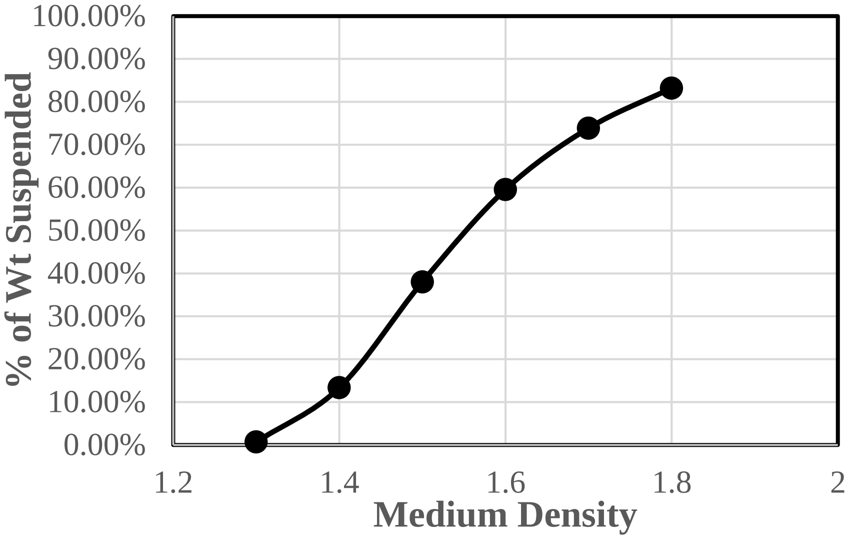

Figure 6.5. Weight of the magnetite suspended changes with medium density

Exploratory no-load testing of the system was performed with the heavy medium only to examine the system function and dependability before coal is fed to the system. Within this process, the medium density of each stream under multiple levels pressure and feed medium density was measured. When the pressure increased, the medium density of product stream and middling stream decreased while an increase occurs in the tailings. With the increasing medium density of the feed, the medium density of each stream changed less sensitively to the pressure which is due to the increasing stability and viscosity of the medium.

Table 6.4. Medium density in each stream under different conditions

Feed Sp.Gr.	Feed Pressure	Product Sp.Gr.	Middling Sp.Gr.	Tailings Sp.Gr.
1.41	-1	1.24	1.42	1.78
	0	1.225	1.41	1.87
	1	1.22	1.37	1.95
1.5	-1	1.355	1.53	1.82
	0	1.335	1.52	1.935
	1	1.315	1.515	1.95
1.6	-1	1.46	1.64	1.86
	0	1.43	1.615	1.965
	1	1.42	1.615	2.05

6.3. Pressure determination and calculation

The commonly used feed pressure for conventional cyclone is 8~10*D. Considering the need for compensating for the head loss in the second stage of the 3-product cyclone in this study, the feed pressure levels were set to be 9*D, 12*D, and 15*D, actually in the industrial plants which apply 3-product cyclones, the pressure can be even higher. Since the Diameter of the pilot scale cyclone is 8”,

$$9 \times 8'' = 72'' of\ water = 2.60 psi\ for\ water$$

When medium is used, the medium density will be considered and the pressure will be 2.60*Sp.Gr psi. Other than that, the height of the pressure gauge above the inlet of the cyclone which is 2.5ft should be considered. Therefore, the final calculations of the pressure gauge readings will be:

Table 6.5. Pressure gauge reading under different pressures

Pressure level	Pressure gauge reading
9*D	2.60*Sp.Gr-1.08*Sp.Gr
12*D	3.46*Sp.Gr-1.08*Sp.Gr
15*D	4.33*Sp.Gr-1.08*Sp.Gr

6.4. System Optimization

The optimum tests were performed under an unchanged condition (Medium Density 1.4, Feed pressure 12*D, M:C=3:1). The only changing parameter was the addition of the slime content. The specific test results were provided in the Results and Discussions section, here provides partition curves for each condition.

Table 6.6. Optimum conditions

Partition Curve No.	Feed Pressure	Medium Density	M:C Ratio	Slime Content	Size Fraction
1	12*D	1.4	3:1	0%	6 × 1mm
2					1 × 0.15 mm
3				10%	6 × 1mm
4					1 × 0.15 mm
5				20%	6 × 1mm
6					1 × 0.15 mm

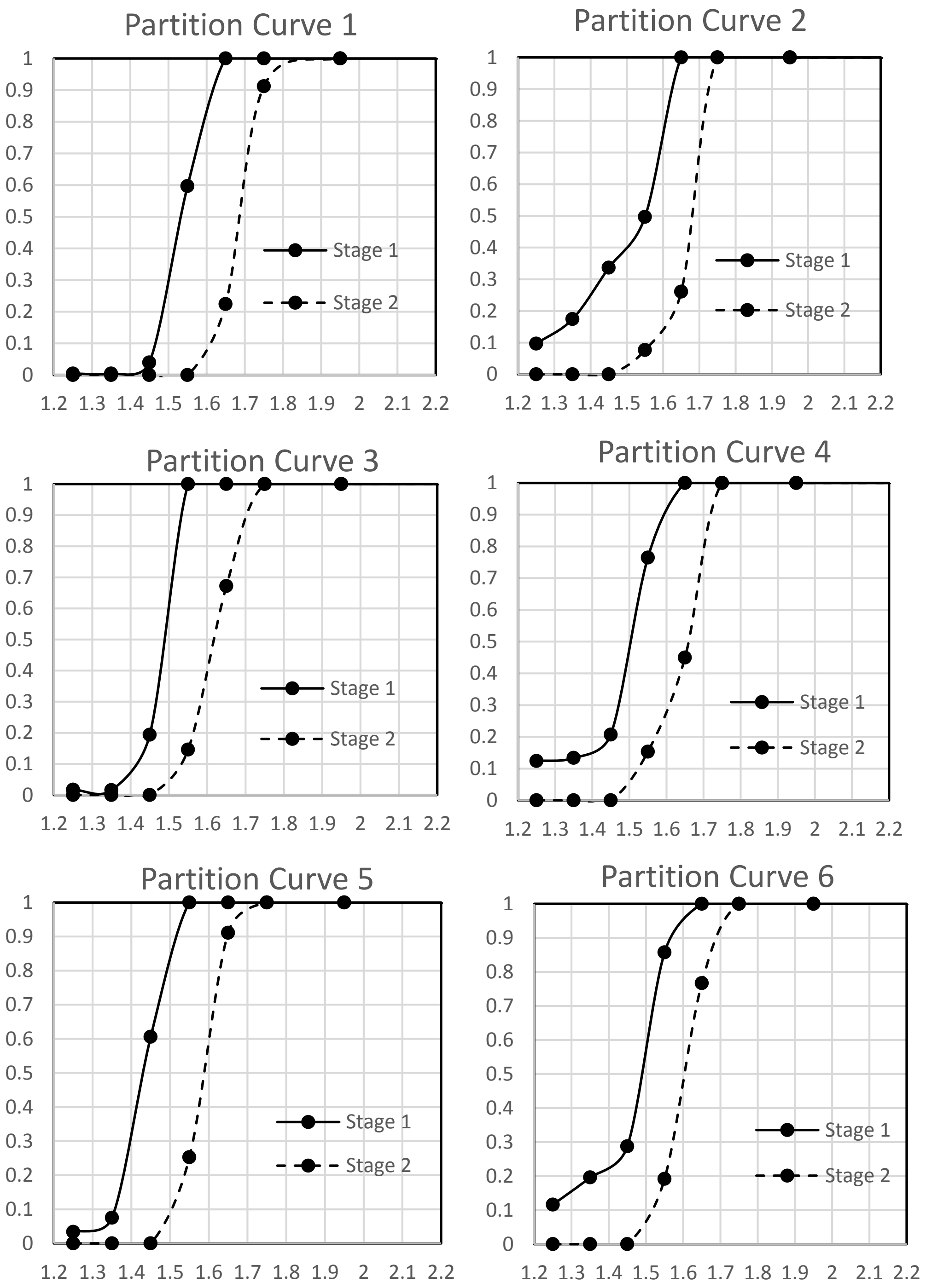

Figure 6.6. Partition Curves under optimum conditions

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