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Project Title:                   **FINE COAL CLEANING WITH AN AUTOMATED  
ENHANCED DENSE MEDIUM GRAVITY CIRCUIT**

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ABSTRACT

The main objective of this project is to automate the operation of the dense medium Falcon concentrator to provide optimal yield and grade with varying feed characteristics.

The Jader coal contains 19.73% ash and 4.09% total sulfur, where as the American coal contains about 28.66% ash having 2.26% total sulfur. Water-injection cyclone experiments were carried out to remove the -325-mesh fraction from the feed coal. The most important parameters of the water-injection cyclone are vortex finder diameter, water-injection rate and spigot diameter for both the Jader and American coals. The truncated cone diameter is a significant parameter for Jader and American coals at 90% confidence level. It was observed that the diameter of the truncated cone should be equal to or more than vortex finder diameter for proper classification. The  $D_{95}$  values are 75 (200 mesh) microns and 45 (325 mesh) microns respectively for with and without water injection. The percentage of -500 mesh and -325 mesh fractions reporting to underflow is 24% and 80% respectively in case of with water injection, where as it is 40% and 92% in case of without water injection.

The dense medium Falcon experiments show that the feed ash and underflow rate have the greatest effect on the product ash content. An increase in feed ash content from 12.77% to 18.44% increased the product ash from about 8% to 10.5% with a decrease in yield from about 92 % to 82%.

Magnetite recovery tests using a high intensity magnetic separator indicate an inability to achieve acceptable levels of separation in a once-flow through operation. However, a rougher-scavenger arrangement of magnetic separators resulted in a separation equivalent to 2.9 lb/ton of magnetite losses.

A semi-automatic control of the dense medium Falcon concentrator was successfully demonstrated. Online measurements of feed ash content and pulp density with the Amdel analyzer were used to maximize product mass yield at a targeted product ash content. This was accomplished using an online constrained optimization routine to control the bowl speed and underflow rate of the Falcon concentrator. An automatic control of the bowl speed was demonstrated while the underflow rate was controlled manually.

## EXECUTIVE SUMMARY

### **Background**

The research conducted during the past two decades on processing of coal fines has changed the description of fine coal as an environmental liability to a material allowing possible economical gains. The development of “Enhanced Gravity Technique” is a product of the research conducted during this period aimed at improving the efficiency of fine particle processing. Research funded in large part by the state of Illinois has shown that enhanced gravity concentration has the ability to improve the rejection of both ash forming minerals and coal pyrite while maximizing the recovery of fine coal. The process efficiently treats particles of sizes of 1 mm, down to as small as 44  $\mu\text{m}$ .

Based on the previous studies conducted at SIU using an enhanced gravity separator called the Falcon Concentrator, it has been observed that though the high centrifugal acceleration helps to achieve efficient separation of finer fraction (-100x325 mesh), it also leads to faster settling of coarser fraction (-28x100 mesh), thus reducing the recovery of coarser coal fraction. Hence, an innovative method was developed at SIUC with the funding provided by ICCI, to improve the separation of coarser coal particles. The method uses dense medium (DM) in the Falcon concentrator thus reducing the effect of size on separation of coal particles. Previous studies with the dense medium Falcon concentrator (DMFC) showed that the separation efficiency depends on the amount of minus 325-mesh present in the feed coal. Also, the efficiency of dense medium operation depends on the feed and media characteristics, which is widely observed in coal preparation plants. Hence, to address these problems studies will be conducted using water-injection cyclone to reduce the fines content in the feed coal and automation of the DM Falcon concentrator to provide an optimal yield and grade for varying feed characteristics.

### **Sample characterization**

The Jader and American coal samples were collected after analyzing the washability data of various coals of Illinois. The samples were subjected to particle size analysis and washability tests and the resulting samples were analyzed for ash, total sulfur and calorific values. The Jader coal contains about 19% ash, having 4% total sulfur. The sample contains around 15% of -400-mesh fraction having an ash and total sulfur contents of about 43% and 6% respectively. The percentage of ash and total sulfur contents increases with decrease in size, indicating the necessity of using an enhanced gravity separator. The American coal contains about 29% ash having 2.26% total sulfur. The amount of -400 mesh fraction is about 28% having an ash content of about 69%.

The washability analysis data on a particle size fraction -16x325 mesh show that the near gravity material within the specific gravity range of 1.5 to 1.8 is in between 1 to 3% for Jader coal and 0.3 to 1.5% for American coal. This finding suggests that the particles are liberated and a moderately efficient gravity separator is sufficient to ensure a high level of combustible recovery. However, since about 35% of the material is between -48x325

mesh fraction it is essential to use an enhanced gravity technique to achieve the required combustible recovery. The theoretical product ash and yield that can be obtained from Jader and American coals respectively are 7% and 85%; and 5% and 90%.

### **Hydrocyclone without water injection**

The hydrocyclone experiments based on the Box-Benkhen design without water injection showed that, for cut point the most important parameters are vortex finder diameter and percent solids. An increase in vortex finder diameter increases the cut point because of higher volumetric flow rate of solids to the overflow, which removes higher fraction of stratified material from the center of the hydrocyclone, thus increasing the cut point. The percent solids also affect the cut point, which increases with increase in percent solids. A feed containing higher percent solids, does not allow the conditions favorable to proper settling of particles, thus increasing the misplacement of coarse fraction to overflow. A lower percent solids level is required for a sharper cut point. As the feed pressure increases, the centrifugal force on the particle increases, thus forcing the particles to move along the wall of the cyclone, which evidently discharged as underflow. Hence, more particles will report to underflow with increase in pressure, which decreases the cut point.

### **Water injection cyclone**

Statistically designed experiments were carried using the Plackett-Burman on the Jader and American coal samples to identify the important variables of the water-injection cyclone. The following parameters were used for the experimental campaign.

- Percent solids (5% - 20 % by weight)
- Feed pressure (10 - 30 psi)
- Vortex finder diameter (0.75 - 1.25 in)
- Spigot diameter (0.6 - 0.9 in)
- Truncated cone diameter (0.75 - 1.0 in)
- Water injection rate (4 - 11 gpm)

The most important parameters of the water-injection cyclone are vortex finder diameter, water-injection rate and spigot diameter for both Jader and American coals. The truncated cone is a significant parameter for Jader coal at 95% confidence level. Where as for American coal the cone is a significant parameter at 90% confidence level. The percent solids do not have much significant effect on the partition number. In normal operation of cyclone the spigot diameter does not have much effect on partition number. Usually, it is expected that the larger the spigot diameter, higher percentage of feed material report to underflow. The feed pressure significantly affects the partition number for the Jader coal, where as for the American coal it does not have much effect. The increase in feed pressure generally increases the centrifugal force, thus providing smaller  $D_{50}$  values. Alias structures for the 8 run Plackett-Burman design show that main effect F (water-injection) is partially confounded with B (feed pressure) and C (vortex finder diameter) two-factor interaction. Based on the analysis of the Plackett-Burman design,

further experiments as per Box-Benkhen design were conducted with the American coal varying vortex finder diameter, water-injection rate and feed pressure.

Based on the Palckett-Burman design tests, experiments were carried out varying Vortex finder diameter, feed pressure and water injection rate. During the experimentation it was observed that a large fraction of the coarse fraction was reporting to the overflow of the cyclone. It was concluded that the ratio of vortex finder diameter to truncated cone diameter is very important. It is preferable to have this ratio one or less than one. Hence, further experiments were carried out keeping the ratio of vortex finder diameter to truncated cone diameter as one, varying water injection rate. The  $D_{95}$  values were 75 microns (200 mesh) and 45 microns (325 mesh) respectively for with and without water injection. The percentage of -500 mesh and -325 mesh fractions reporting to underflow is 24% and 80% respectively in case of with water injection, where as it is 40% and 92% in case of without water injection. The water injection slightly increases the cut point, while reducing the percent of fines in the underflow. This study clearly shows that the water injection at the apex of the cyclone reduces the fines content in the underflow.

### **Dense medium Falcon**

Statistically designed experiments were carried using the Box-Benkhen design on the American coal to quantify the effects of the operating parameters associated with the dense medium-based Falcon using the following operating parameters.

- Feed ash (7% – 20%)
- Bowl speed, (20 – 40 Hz)
- Tailings underflow rate (5 lpm – 15 lpm)

The results of the dense medium Falcon tests show that feed ash and underflow rate have the greatest effect on product ash content. The curvilinear nature of the product ash curve suggests that the product ash is a strong quadratic function of underflow rate, which is supported by a relatively low t-statistic obtained for  $C^2$  term. The increase in feed ash increases the product ash with decrease in yield. An increase in feed ash content from 12.77% to 18.44% increased the product ash from about 8% to 10.5% with a decrease in yield from about 92 % to 82%. Hence, the change in feed properties significantly affects the process performance. Therefore, it is necessary to automate the dense medium Falcon to maximize the product yield for a given product ash content for varying feed properties. The higher bowl speed increases the centrifugal force, thus providing accumulation of magnetite particle near the wall of bowl. This process increases the specific gravity of cut increasing the product ash and with a marginal increase in yield.

### **Magnetite Recovery**

Magnetite recovery from the dense medium Falcon concentrator clean coal product was evaluated. Statistically designed experiments were conducted on a laboratory Eriez L-8 wet drum separator to evaluate the influence of flow rate, magnetic intensity, pulp density and magnetic loading on the separation performance. Experiments were conducted as a

single stage operation as well as in a rougher-scavenger arrangement. The experimental results indicate that the magnetite recovery efficiency increases with a decrease in flow rate. The efficiency is seen to improve with an increase in magnetic efficiency. Pulp density and magnetite loading interactively influence the separation performance.

A single stage operation resulted in an inferior performance resulting in a magnetite loss of approximately 35 lb/ton (lbs of magnetite/ton of coal). This is a result of the fineness of the magnetite used in the dense medium falcon cleaning operation. However, a rougher-scavenger operation was able to achieve a separation performance equivalent to 3 lb/ton of magnetite loss.

### **Dense medium Falcon Automation**

An Amdel Coal Slurry Analyzer (CSA) was installed at the high-bay facilities at SIU. The CSA was calibrated to measure the ash content and solids percent in a fine coal slurry. Since the CSA uses a metal scatter channel for measurement, it was possible to use the CSA to measure the ash and solids percent for a fine coal slurry containing magnetite. The measurement accuracy achieved for ash content was  $\pm 1.25\%$  and that for solids percent was  $\pm 0.75\%$ .

A control system was developed that responded to changes in feed quality by changing the operating parameters (bowl speed and underflow rate) of the Falcon concentrator to maintain the targeted product quality (ash content) while simultaneously maximizing the mass yield. Automatic control of the bowl speed was implemented while a manual control for the underflow rate was used. Manual control for the underflow rate was necessitated due to a lack of correlation between the actual underflow rate and the air pressure used to control the same. Also, measurement of the underflow rate was difficult due to the high density and flow characteristics of this stream.

The control system was demonstrated by disturbing the ash content of the Falcon concentrator while in operation. The Amdel analyzer, measuring the ash content every minute, detected the change in ash content and transmitted the reading to its control computer. The Falcon concentrator control computer polled the Amdel computer once every minute. Upon receipt of the changed ash content value by the Falcon concentrator computer, an optimization routine was automatically initiated that determined the bowl speed and underflow rate settings required to maximize the product yield while maintaining the product quality constraints for the observed change in the feed quality. The new setting for bowl speed was transmitted to the Falcon controller for automatic adjustment of the bowl speed. The new underflow rate setting was displayed on the computer screen prompting the operator to manually adjust the underflow rate.

A series of eight tests was carried out under artificially varied feed ash contents from 13% to 25%. The target ash content level was varied from 10% to 12%. The actual yield and ash contents as calculated from the feed, product and tailings assays matched very well with those predicted by the online control optimization routine.

## OBJECTIVES

The overall goal of the proposed project is to develop an advanced automated dense medium fine coal cleaning technology that provides a significant improvement in the separation efficiency currently achieved from the treatment of fine coal, while maintaining the economics of the process. In addition to providing a higher product quality while maximizing energy recovery, the process must have a relatively high capacity and be amenable to on-line control for plant optimization purposes. A successful test program to develop the heavy media application with the Falcon concentrator for fine coal processing will meet the aforementioned project goal. The specific project objectives are:

- Evaluate and optimize the performance of the dense medium Falcon operation for coals of different characteristics;
- Development of a control strategy to adjust the DMFC parameters to varying operating conditions to maximize the separation efficiency.
- Study the performance of Cylowash on the removal of –325 mesh particles.
- Study the effect of magnetite medium properties on the performance of the dense medium Falcon operation.
- Perform a preliminary evaluation of media loss and develop appropriate schemes for a magnetite recovery circuit.
- Perform an economic evaluation of the proposed circuit

The tasks required to achieve these objectives are summarized below:

### **Task 1. Coal and Magnetite Sample Collection and Characterization**

Coal samples from the fine coal circuit were collected in 55gallon drums. The samples were homogenized and a representative sample was prepared for each coal for characterization. The representative sample was characterized on particle size-by-size and density-by-density. The magnetite required for the test work in this investigation was obtained from a commercial producer. Upon arrival, the particle size distribution of the magnetite was evaluated.

### **Task 2. Evaluation of Water-injection cyclone**

The object of this task is to remove –325-mesh fraction from the feed slurry coal using a water-injection cyclone. The important variables were identified and optimized for maximum removal of –325-mesh fraction.

### **Task 3. Experiments on Dense Medium Falcon Concentrator (DMFC)**

In this task, the effects of the operating parameters associated with the dense medium-based Falcon were quantified using a statistically designed experimental program on one of the coal slurry samples prepared in Task 1.

#### **Task 4. Product Analysis and Process Optimization**

Empirical relationships were developed using the experimental data for providing maximum yield over a range of ash were quantified. These relations were used for calculation of optimum values for process control.

#### **Task 5. Process Automation and Control**

The aim of this task was to develop a control strategy for the Falcon Concentrator, using an on-line coal slurry analyzer to adjust its design parameters suitably to varying feed characteristics. A semi-automatic control was successfully implemented and demonstrated to effectively achieve optimal separation efficiency for the Falcon concentrator under varying feed qualities.

#### **Task 6. Evaluation of a Media Recovery Circuit**

The aim of this task was to develop an efficient magnetic recovery circuit using Magnetic Separators. To evaluate the effect of media and contaminant loading on magnetic separation, a series of laboratory tests were conducted. Based on these results, a rougher-scavenger circuit configuration was tested and found to provide adequate magnetite recovery performance.

#### **Task 7. Reporting**

Reports were submitted as per Illinois Clean Coal Institute guidelines.

### INTRODUCTION AND BACKGROUND

Due to the increased mechanization of underground coal mining, the proportion of fine coal reporting to the coal processing plants has increased from approximately 5% to about 20% of the overall run-of-mine production. It has also been a trend in the industry to increase the top size being fed to the fine coal cleaning circuit from about 28 mesh to 10 mesh in order to reduce the load on the intermediate circuits or to allow processing of the entire +10 mesh fraction using a single unit operation. However, this trend will ultimately result in a higher fraction of the feed coal reporting to the fines circuit, which has used relatively inefficient separation techniques in the past. Hence, some coal processing plants prefer to dispose the entire fine coal fraction.

Southern Illinois University has been actively engaged in evaluating and optimizing the performance of enhanced gravity separation technologies with the help of research funding from the Illinois Clean Coal Institute (ICCI), Illinois coal companies and equipment manufacturers. Based on initial laboratory and pilot-plant studies, successful in-plant trials of the advanced fine coal cleaning technologies were conducted. The in-plant trials have shown a significant improvement in the fine coal cleaning circuit performance by using advanced clean coal technologies. The ability of dense medium

falcon to achieve efficient low gravity cut-points has been successfully demonstrated with the help of funding support provided by ICCI.

This pilot-scale study of the DMFS revealed that the separation efficiency is very sensitive to the presence of the percentage of –325-mesh size fraction in the feed. The most practical method for the removal of –325-mesh size fraction is to utilize hydrocyclone. However, the conventional cyclones do not provide better classification efficiency due to the bypass of feed material to the underflow. At least 10% to 25% of very fine particles report to underflow. Hydraulic water addition through the apex, to displace the underflow liquid has been used to increase the sharpness of separation. Hence, one of the main aims of this project was to study the effect of water-injection in the removal of fine particle.

Another problem faced by today's coal preparation plants is the wide fluctuations encountered in the feed coal properties in terms of the ash content as well as the washability characteristics. The fluctuation in the plant feed ash content is caused by the out-of-seam dilution during the mining operation, while the change in the washability characteristics occurs typically in preparation plants treating feeds from multiple sources. Therefore, processes that can effectively handle wide variations in feed characteristics and provide efficient separations at high mass yield are required to maximize mine profitability. Thus, it is imperative to use an automation and control strategy that can respond quickly to any change in the feed characteristics. Therefore, the main aim of this study was to develop an efficient enhanced gravity separation circuit addressing the important problems faced in the fine coal processing.

## EXPERIMENTAL PROCEDURES

### **Test Samples**

Coal samples from the feed to the cyclone were collected from the Jader and Galatia coal preparation plants. The composite feeds to the cyclone were collected in 55 gallon barrels and 15-20 barrels of sample were collected from each plant.

### **Sample Preparation**

The samples contained a significant portion of +16 mesh fraction. As this study is directed towards fine coal cleaning, the +16 mesh fraction was removed from both the samples using wet screening.

Since the samples were collected during a period of time, it was necessary to homogenize the samples to obtain a representative sample for the experimental study. In this investigation sample preparation was accomplished by mixing the material into a slurry state by the addition of water. For this purpose, a large 2000-gallon mixing tank was employed along with a 5 hp pump to extract the slurry through an underflow discharge point. To ensure representative splitting of the sample, the pump discharge was cycled



around different barrels, which were protected with a liner, using an equal time interval for each barrel.

### **Representative Sampling**

Representative samples (around 5 gallons) were withdrawn from each barrel and were further reduced using a rotary slurry splitter. The representative samples obtained from the slurry splitter were used to verify an equal split of sample in each barrel and for all the sample characterization including gravity washability and release analysis tests. The remaining sample from the rotary splitter was returned to the respective barrel of origin.

The average ash content is 19.73% and 29.64% with a standard deviation of 1.10 and 1.63 between samples respectively for Jader and American coals. Therefore, all barrels were assured to possess similar properties and hence a representative bulk sample was prepared by combining the same amount of material from each barrel. The sample was subjected to particle size analysis using the wet sieving technique.

### **Water-Injection Cyclone Test Rig.**

The water-injection cyclone test equipment requires a unique method to enable collection of the overflow and underflow products of the cyclone. When there is no injection of water to the cyclone, the underflow and overflow of the cyclone can be recirculated. However, upon injection of water to the cyclone, the overflow and underflow have to be redirected to a separate vessel to avoid the dilution of the feed to the cyclone and also be able to collect representative samples.

Hence, to achieve the above-mentioned goal a special sample collection method has been devised. The sampler was fabricated using metal sheets, which diverts the underflow and overflow of the water-injection cyclone to sampling containers. It is also possible to collect both streams simultaneously for a given period of time. The water-injection equipment also contains two flow meters to measure feed flow rate and injected water flow rate to the cyclone.

### **Experiments with the Water-injection Cyclone**

The water-injection cyclone experiments with Jader and American coal samples were conducted using the Krebs–Cyclowash. The schematic diagram of the experimental setup is shown in Figure 1. The feed coal to the cyclone (-16 mesh) was prepared by screening coal samples to remove +16 mesh fraction. The cyclone was fitted with the required diameters of vortex finder, spigot and truncated cone. Prior to each test, the feed sump was filled with a measured quantity of water and the required quantity of coal sample. The slurry in the feed sump was kept in suspension using stirrers and a re-circulation circuit. After measuring the feed density, the desired feed pressure was set by adjusting the by-pass valve. Required amount of water is injected to the cyclone. While injecting water, the cyclone overflow and underflow were redirected to another tank to avoid dilution of the feed sample. The feed, cyclone underflow and overflow were collected

simultaneously, using the fabricated sample cutter. The samples collected were weighed to find out the percent solids and were subjected to detailed wet sieve analysis. The samples from the wet screen analysis were weighed and analyzed for ash and total sulfur contents using ASTM procedures.

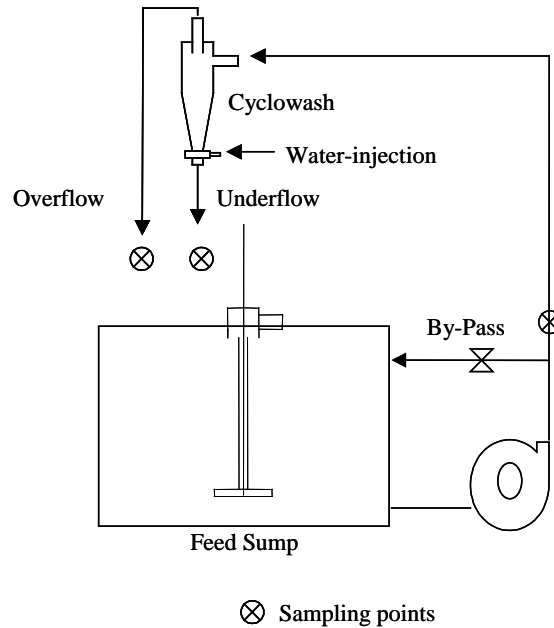


Fig. 1 Schematic representation of the Cyclowash test rig

## Magnetic Separation

The magnetic separation experiments were carried out the University of Kentucky. The magnetic separator used to evaluate magnetite recovery in this investigation was an Eriez L-8 laboratory wet drum unit. The unit was operated in a continuous mode at flow rates up to 8 gallons/minute. The unit was operated in a co-current arrangement where the slurry flow through the separator is in the same direction as the magnetic drum rotation. This arrangement ensures maximum magnetite recovery. The drum was 12 inches in diameter and 7.5 inches wide and had a rotational speed of 50 rpm. An electromagnetic element was used which allowed adjustment of the magnetic field intensity through control of the applied D-C voltage.

The magnetite-coal feed slurry was placed in a 30-gallon sump. A recirculation pump was used to agitate the slurry and maintain a suspension. Representative samples of the feed were taken from the recirculation line. A peristaltic pump was used to feed the magnetic separator from a location close to the pump discharge. The feed to the magnetic separator (magnetite + coal) was prescreened at 65 mesh for removal of the coarse magnetite which could have led to destabilization of the magnetic suspension.

A set of 10 statistically designed experiments were conducted to study the influence of feed volumetric flow rate, magnetic field intensity and feed pulp density on the magnetite recovery performance. In addition 4 experiments were conducted to evaluate the response of the separator to varying levels of magnetite loading. One additional test was conducted to evaluate the performance in a rougher – scavenger arrangement.

For each experiment, the magnetic concentrate and non-magnetic stream was analyzed for magnetics content using the Davis Tube.

### **Automation and Control**

The automation of the Falcon concentrator requires continuous analysis of feed or product streams. The developed algorithm to control the critical operating parameters of the Falcon concentrator to achieve the desired product quality and quantity uses this information. An AMDEL on-line coal slurry analyzer (CSA), which was developed in Australia, was used at SIU for online measurement of the fine coal feed slurry ash and solids content. The CSA was used on both the water-only and magnetite containing slurries. Calibration equations were developed for both these cases over varying ranges of ash contents and solids contents. Calibration equations were developed using the following parameters.

- Scatter – X-ray
- Neutron count rate
- Fe correction
- Aeration
- Temperature

A Levenberg-Marquardt gradient search algorithm was implemented to perform a constrained optimization routine in realtime, which identified the operating conditions (Bowl speed and underflow rate) that provided the maximum product yield for any given product quality constraint.

A set of eight experiments was conducted varying the feed ash content going to the Falcon concentrator while keeping the feed solids percent constant. The change in feed ash content was achieved by addition of another high ash content sample to the Falcon feed sump while continuously operating the Falcon. The change in ash content was detected by the CSA and transmitted to the control computers. The optimization routine was initiated in realtime, which, in turn, automatically controlled the bowl speed. The computer simultaneously prompted the operator to manually adjust the underflow rate as and when needed.

The control circuit was implemented as shown in Figure 2.

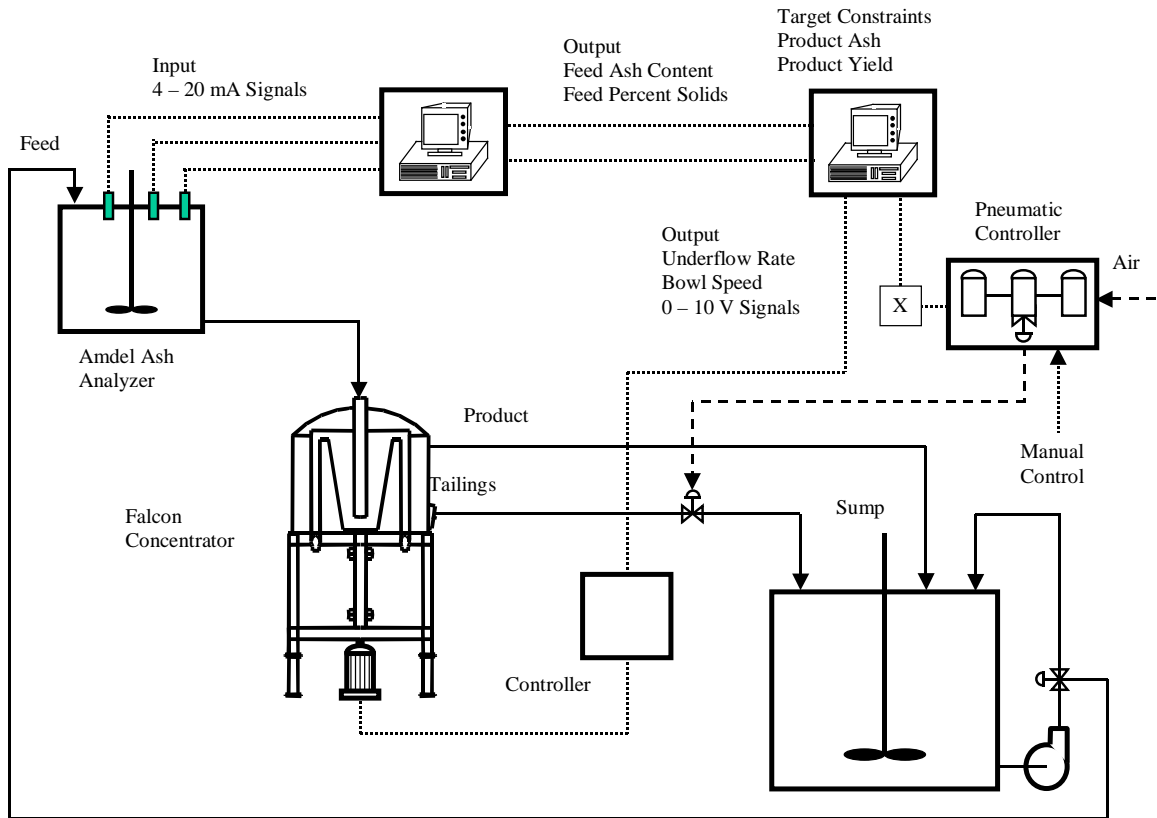


Figure 2. Schematic diagram of the automation of the Falcon concentrator.

## RESULTS AND DISCUSSION

### Selection of Sample

The efficiency of water-only process reduces with increase in near gravity material and the amount of fines present in the coal sample. The enhanced dense medium Falcon concentrator is more efficient than the water-only Falcon concentrator. Hence, it is necessary to select coal samples, which are difficult to clean using water-only process, to take advantage of the enhanced dense medium Falcon concentrator. The previous washability data of different coals were analyzed to select coal samples for the present work.

The washability data for coals from Galatia, Marissa, Wabash and Jader Fuel ( $\approx -16$  mesh) were analyzed to select two coal samples for the current work. The ROM coal of Galatia mine contains about 14% (by wt.) of  $-16$ -mesh coal, having an ash content of 26%. The near gravity material (NGM) in the region 1.4 to 1.8 densities ( $\text{gm}/\text{cm}^3$ ) is about 3%. The presence of lower amount of NGM indicates that a moderately efficient process may be used to clean the coal. However, the presence of high amount of fines indicates that the coal requires an efficient gravity separator.

The ROM coal from Marissa mine contains about 42% (by wt.) of –16-mesh fraction having an ash content of 25%. The NMG in the density range 1.4 to 1.8 is about 4 to 6%, requiring an efficient separator for the cleaning of this coal. In the case of Wabash coal, the ROM contains about 10% (by wt.) -16-mesh fraction having an ash content of about 7%. The NMG in the density range 1.4 to 1.8 is around 1%. Therefore, a moderately efficient separator may be utilized for the cleaning this coal. The washability data on composite Jader Fuel feed to cyclone (seams 2+3) indicates that the –16 mesh sample contains about 21% ash. The NMG in the density range 1.4 to 1.8 is about 4 to 17%. Hence, this coal requires an efficient separator for cleaning.

The above analyses show that coal samples from Galatia, Marissa and Jader Fuel mines are good candidates for use in this study. Of these, samples were collected from Jader and Galatia coal preparation plants.

### Characterization of Jader and American Samples

Bulk sample obtained for Jader feed to cyclone was subjected to particle size analysis using the wet sieving technique. The material collected in each particle size fraction was subsequently analyzed for ash, total sulphur and calorific value contents. For the calorific value determination, a LECO AC-350 Model BTU analyzer was used. The reference samples used were the LECO Series 501 bituminous coal samples, which have been standardized in accordance with ASTM D-3286 isoperibol calorimetry. The results are presented in Tables 1 and 2.

Table 1. Size by size ash and total sulfur analysis of Jader coal sample

Size fraction (mesh)	Weight (%)	Ash (%)	Total Sulfur (%)
+16	2.36	9.48	3.33
16x28	20.05	9.85	2.90
28x48	25.17	10.07	3.01
48x65	10.92	11.68	3.30
65x100	9.51	14.52	3.43
100x200	10.49	25.26	4.58
200x325	4.78	44.22	7.60
325x400	1.58	46.34	7.96
400x500	2.20	44.43	10.50
-500	12.93	42.93	5.41
TOTAL	100.00	19.42	4.00

Table 2. Size by size ash and total sulfur analysis of American coal sample

Size fraction (mesh)	Weight (%)	Ash (%)	Total Sulfur (%)
+16	0.16	5.14	1.34
16x28	14.04	4.66	1.45
28x48	19.64	4.83	1.51
48x65	9.34	6.21	1.70
65x100	8.92	6.96	1.72
100x200	11.90	15.25	2.15
200x325	5.47	57.17	2.55
325x400	2.28	65.40	2.86
400x500	3.50	68.74	2.98
-500	24.74	68.72	2.95
TOTAL	100.00	28.66	2.26

The Jader coal contains about 19% ash, having 4% total sulfur. The sample contains around 15% of –400-mesh fraction having an ash and total sulfur contents of about 43% and 6% respectively. The percentage of ash and total sulfur contents increases with decrease in size, indicating the necessity of using an enhanced gravity separator. The American coal contains about 29% ash having 2.26% total sulfur. The amount of –400 mesh fraction is about 28% having an ash content of about 69%.

Washability analysis was conducted on -16x325 size fraction of the Jader and American coal samples. The analysis was conducted using the ASTM static bath procedure and lithium metatungstate solution as the medium. Each density fraction was rinsed, dried and prepared for ash and total sulfur analyses. The results of the washability tests regarding respective size fractions are presented in Table 3 and 4.

Table 3. Washability data for -16 x325 mesh Jader coal

Specific gravity fraction	Individual			Cumulative		
	Weight (%)	Ash (%)	Combustible Recovery (%)	Weight (%)	Float Ash (%)	Combustible Recovery (%)
1.3	62.55	5.45	68.87	62.55	5.45	68.88
1.3X1.4	17.09	9.34	18.05	79.64	6.28	86.93
1.4X1.5	5.88	16.09	5.75	85.52	6.96	92.68
1.5X1.6	2.94	21.74	2.68	88.46	7.45	95.35
1.6X1.7	1.20	26.83	1.02	89.66	7.71	96.37
1.7X1.8	0.98	31.30	0.78	90.64	7.96	97.16
1.8X2.1	1.52	40.71	1.05	92.16	8.51	98.21
2.1	7.84	80.41	1.79	100.00	14.14	100.00
Total	100.00	14.14	100.00			

Table 4. Washability data for -16 x325 mesh American coal

Specific gravity fraction	Individual			Cumulative		
	Weight (%)	Ash (%)	Combustible Recovery (%)	Weight (%)	Float Ash (%)	Combustible Recovery (%)
1.3	67.36	5.45	73.58	67.36	5.45	73.58
1.3X1.4	17.41	9.34	18.23	84.77	6.25	91.81
1.4X1.5	4.10	16.09	3.98	88.87	6.70	95.79
1.5X1.6	1.42	21.74	1.28	90.29	6.94	97.07
1.6X1.7	0.44	26.83	0.37	90.73	7.04	97.44
1.7X1.8	0.35	31.30	0.28	91.08	7.13	97.72
1.8X2.1	0.57	40.71	0.39	91.65	7.34	98.11
2.1	8.35	80.41	1.89	100.00	13.44	100.00
Total	100.00	13.44	100.00			

It is clearly evident from the washability data of Jader coal that the clean coal yield is about 85% having an ash content of 7% at an average density of 1.45%. Increasing the density to 1.55 increases the yield by about 2.5%, slightly increasing the product ash content to 7.4%. At a density of 1.85 it is possible to obtain a clean coal having an ash content of 8.5 with 92% yield. However, in practice maintaining a density of 1.85 is not practical due to increased viscosity of the slurry and other handling problems. Similarly, for American coal at a medium density of 1.45 the product yield is about 90% having about 5% ash.

It is clearly evident from Tables 3 and 4 that the near gravity material within the specific gravity range of 1.5 to 1.8 is in between 1 to 3% for Jader coal and 0.3 to 1.5% for American coal. This finding suggests that the particles are liberated and a moderately efficient gravity separator is sufficient to ensure a high level of combustible recovery. However, since about 35% of the material is between -48x325 mesh fraction it is essential to use an enhanced gravity technique to achieve the required combustible recovery.

### **Evaluation of Water-injection cyclone**

#### *Experiments without water-injection*

Even though this task is not proposed in the original project proposal, hydrocyclone (without water-injection) experiments were conducted using American coal to compare the classification efficiency with and without water injection. The water-injection cyclone was used for these tests, after removing the truncated cone and wash water attachment. The spigot is used to discharge the underflow solids at the maximum possible density, without rope discharge. The effect of spigot diameter on the separation is minimal, if there is no constriction of the underflow discharge. Hence, a constant spigot diameter was used for these tests. A statistically designed set of experiments using Box-Benken

design was conducted on the hydrocyclone cyclone to study the effect of the following variables.

- Percent solids (5% to 20 % by weight)
- Feed pressure (10 psi to 30 psi)
- Vortex finder diameter (0.75 in – 1.25 in)

The test conditions and response are given in Table 5 for American coal. The test data (Table 5) was analyzed using Design Expert software. The mesh of separation or  $D_{95}$  is the particle size, which has a 95% chance of reporting to underflow. This is often called as the cut point. The  $D_{50}$  is the particle size which has a 50% chance of reporting to the cyclone underflow. The  $D_{50}$  is generally used to model the cyclone. Empirical model describing the cut point ( $D_{95}$ ) as a function of the operating parameter values can be written for American (Eq. 1) coal as,

$$D_{95} = 34.11 + 5.88 \times A - 5.37 \times B + 11.75 \times C + 7.89 \times C^2 - 10.00 \times B \times C \quad [1]$$

in which  $A$  is the Percent Solids (% by weight),  $B$  Feed Pressure (psi) and  $C$  Vortex Finder Diameter (inch). The equations are presented in coded form in which value ranges of  $-1$  to  $1$  represents each parameter.

The coefficients of Eq. [1] and their significance are provided in Table 6. Table 6 shows that, for cut point the most important parameters are vortex finder diameter and percent solids. The effect of each parameter on the cut point is pictorially depicted in the perturbation graph (Fig. 3). The quadratic nature of the curve  $C$  shows that the vortex finder diameter is an important parameter. This conclusion is supported by the very low value of  $t$ -statistic. An increase in vortex finder diameter increases the cut point, because of higher volumetric flow rate of solids to the overflow, which removes higher fraction of stratified material from the center of the hydrocyclone, thus increasing the cut point. The percent solids also affect the cut point, which increases with increase in percent solids. A feed containing higher percent solids, does not allow the conditions favorable to proper settling of particles, thus increasing the misplacement of course fraction to overflow. A lower percent solids is required for a sharper cut point. As the feed pressure increases, the centrifugal force on the particle increases, thus forcing the particles to move along the wall of the cyclone, which discharged as underflow. Hence, more particles will report to underflow with increase in pressure, which decreases the cut point. Table 6 also shows that there is significant interaction between feed pressure and vortex finder diameter.

At a feed pressure of 10 psi and vortex diameter of 1.25 inch the cut point is 69 microns. However, at the same vortex finder diameter of 1.25 inch, an increase in feed pressure from 10 psi to 30 psi decreases the cut point from 69 microns to 41 microns. This decrease in cut point is mainly due to the increase in centrifugal force at higher feed pressure, which forces the particles to discharge through underflow.

Equation 1 was used to optimize the cut point for achieving maximum classification efficiency. A steepest ascent/descent optimization routine was utilized to



maximize/minimize the desirable merit function for simultaneous optimization of multiple responses. The goal was to achieve the cut point of 45 microns. By changing the criteria used to achieve the goal, it was possible to obtain conditions for factors under which a cut point of 45 microns could be obtained. These conditions are tabulated in Table 7.

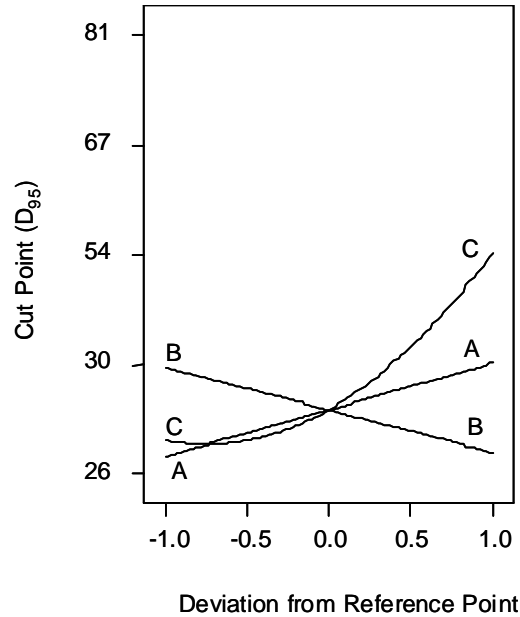


Figure 3. Perturbation plots showing the parameter effects on cut point. (American coal).

Table 5. The test design matrix and responses for the Box–Benkhen test program conducted on the hydrocyclone using the American coal.

Run No.	Percent Solids (wt%)	Feed Pressure (psi)	Vortex Finder Diameter (in)	Cut Point, D <sub>95</sub> (microns)
1	5	10	1	26
2	20	10	1	42
3	5	30	1	31
4	20	30	1	36
5	5	20	0.75	28
6	20	20	0.75	32
7	5	20	1.25	36
8	20	20	1.25	58
9	12.5	10	0.75	31
10	12.5	30	0.75	30
11	12.5	10	1.25	81
12	12.5	30	1.25	40
13	12.5	20	1	32
14	12.5	20	1	32
15	12.5	20	1	35
16	12.5	20	1	38
17	12.5	20	1	35

Table 6. Least square coefficients of the model equation for  $D_{95}$ , (American coal)

Factor	Coefficient	Prob >  t	VIF
Intercept	34.11	0.0011	
A-Percent Solids	5.88	0.0361	1
B-Feed Pressure	-5.37	0.0515	1
C-Vortex Finder	11.75	0.0006	1
$C^2$	7.89	0.0397	1
BC	-10.00	0.0152	1

Table 7 shows that at lower feed pressures (B), the model suggest to use a vortex finder of smaller diameter, where as at a higher feed pressure (24.60 psi) it is necessary to use a larger vortex finer to achieve the same cut point. As explained earlier, for a given vortex finder diameter, the higher pressure decreases the cut point. The partition data shows that about 40% (corrected 19%) of 500 mesh (average size 12.5 micron) fraction present in the feed reports to underflow. Where as about 90% of 41 micron fraction reports to underflow. This data clearly shows the large amount of very fine particles short-circuiting to the underflow fraction.

Table 7. Optimized factor levels to be maintained in order to achieve target cut point of 45 microns. (American coal)

Run No.	Factor			$D_{95}$	Desirability
	A	B	C		
1	18.48	10.96	1.02	44.96	1
2	7.16	15.25	1.15	44.99	1
3	13.12	24.60	1.23	45.02	1

#### *Water-injection cyclone (Plackett-Burman design)*

A statistically designed set of experiments using Plackett-Burman design was conducted on the water-injection cyclone to identify the most significant operating variables. The variables and their respective value range used for the statistical design were:

- Percent solids (5% - 20 % by weight) (A)
- Feed pressure (10 - 30 psi) (B)
- Vortex finder diameter (VFD) (0.75 - 1.25 in) (C)
- Spigot diameter (0.6 - 0.9 in) (D)
- Truncated cone diameter (TCD) (0.75 - 1.0 in) (E)
- Water injection rate (4 - 11 gpm) (F)

Analysis of the design shows that the Design-Expert calculates alias patterns for all Plackett-Burman designs. Alias structures for the 8 run designs are complex, because each main effect is partially confounded with several two-factor interactions. Hence, the

Plackett-Burman design based on 8 experiments gives only general idea about the significance of the parameters if the two factor interactions are significant.

### Analysis of data

The Plackett-Burman design and responses are given in Table 8 and 9 for Jader and American coals respectively. The analyses of the Plackett-Burman data using  $D_{50}$  or  $D_{95}$  showed no significance of the parameters. This may be due to the confounding of main effects with two or three factor interactions, as explained earlier. Since, our main aim of conducting water-injection cyclone tests is to remove the minus 325-mesh fraction, the test data was analyzed using the percentage of minus 325-mesh fraction reporting to underflow as the response variable.

Empirical models describing the partition number (defined as, percent of feed at -325 mesh reporting to underflow), as a function of the operating parameter values can be written respectively for Jader (Eq. 2) and American (Eq. 3) coals as,

$$\text{Partition number} = 76.48 - 3.88 \times B - 14.85 \times C + 4.00 \times D + 2.18 \times E - 5.50 \times F \quad [2]$$

$$\text{Partition number} = 81.35 - 1.85 \times A + 0.90 \times B - 9.45 \times C + 4.10 \times D + 1.95 \times E - 3.80 \times F \quad [3]$$

in which  $A$  is the Percent Solids (% by weight),  $B$  Feed Pressure (psi),  $C$  Vortex Finder Diameter (inch),  $D$  Spigot Diameter (inch),  $E$  Truncated Cone (inch),  $F$ -Water-injection rate (gpm). The equations are presented in coded form in which values range of  $-1$  to  $1$  represents each parameter.

Table 8. Plackett-Burman experimental program used to identify operating parameters having a significant impact on the removal of  $-325$  mesh fraction from cyclone underflow. (Jader coal)

Run No.	Percent Solids (by wt%)	Feed Pressure (psi)	Vortex Finder Diameter (in)	Spigot Diameter (in)	Truncated Cone Diameter (in)	Water Injection Rate (gpm)	Percentage of -325mesh present in the feed to underflow
	A	B	C	D	E	F	
1	5	10	0.75	0.9	1.00	11	96
2	20	10	0.75	0.6	0.75	11	83
3	5	30	0.75	0.6	1.00	4	90
4	20	30	0.75	0.9	0.75	4	95
5	5	10	1.25	0.9	0.75	4	72
6	20	10	1.25	0.6	1.00	4	70
7	5	30	1.25	0.6	0.75	11	46
8	20	30	1.25	0.9	1.00	11	57

Table 9. Plackett-Burman experimental program used to identify operating parameters having a significant impact on the removal of -325-mesh fraction from cyclone underflow. (American coal)

Run No.	Percent Solids (by wt%) A	Feed Pressure (psi) B	Vortex Finder Diameter (in) C	Spigot Diameter (in) D	Truncated Cone Diameter (in) E	Water Injection Rate (gpm) F	Percentage of -325mesh present in the feed to underflow
1	5	10	0.75	0.9	1	11	94
2	20	10	0.75	0.6	0.75	11	84
3	5	30	0.75	0.6	1	4	97
4	20	30	0.75	0.9	0.75	4	96
5	5	10	1.25	0.9	0.75	4	78
6	20	10	1.25	0.6	1	4	74
7	5	30	1.25	0.6	0.75	11	74
8	20	30	1.25	0.9	1	11	73

The actual and predicted values for partition number using Equations 2 and 3 yielded  $R^2$  value of 0.99. The coefficients of Eqs. [2] and [3] and their significance are provided in Tables 10 and 11. The associated p-values ("Prob > |t|") are interpreted as the probability of realizing a coefficient as large as that observed, when the true coefficient equals zero. In other words, small values of  $p$  (less than 0.05) indicate significant coefficients in the model. The variance inflation factor (VIF) measures how much the variance of the model is inflated by the lack of orthogonality in the design. If the factor is orthogonal to all the other factors in the model, the VIF is 1.0. Table 10 and 11 show that, for partition number, the most important parameters are vortex finder diameter, water-injection rate and spigot diameter for both coals. The truncated cone is a significant parameter for Jader coal at 95% confidence level. Where as for American coal the cone is a significant parameter at 90% confidence level. The percent solids do not have much significant effect of the partition number. In normal operation of cyclone the spigot diameter does not have much effect on partition number. Usually, it is expected that the larger the spigot diameter, higher percentage of feed material report to underflow. Hence, to increase the  $D_{50}$  a spigot having smaller diameter may be used for further experiments. The feed pressure significantly affects the partition number for Jader coal, where as for American coal it does not have much effect. The increase in feed pressure generally increases the centrifugal force, thus providing smaller  $D_{50}$  values. Alias structures for the 8 run Plackett-Burman design show that main effect F (water-injection) is partially confounded with B (feed pressure) and C (vortex finder diameter) two-factor interaction. Hence, it is decided to vary this parameter in further experiments.

It can be concluded that vortex finder diameter and water-injection rate significantly affect the partition number for both coals. The percent solids does not appear to have effect on classification performance of Jader and American coals in the range studied. The feed pressure significantly affects the Jader coal, where as it does not affect the

American coal. This probably may be due the presence of higher percentage of clay particles (around 23%) compared to Jader coal (around 10%), which may affect the classification.

Table 10. Least square coefficients of the model equation for partition number.  
(Jader coal)

Factor	Coefficient	Prob >  t	VIF
Intercept	76.475	0.0042	1
B-Feed Pressure	-3.875	0.0156	1
C-Vortex Finder	-14.85	0.0011	1
D-Spigot	4.0	0.0146	1
E-Truncated cone	2.175	0.0470	1
F-Water-injection	-5.5	0.0078	1

Table 11. Least square coefficients of the model equation for partition number.  
(American coal)

Factor	Coefficient	Prob >  t	VIF
Intercept	81.35	0.0331	
A-Percent Solids	-1.85	0.0686	1
B-Feed Pressure	0.9	0.1392	1
C-Vortex Finder	-9.45	0.0135	1
D-Spigot	4.1	0.0310	1
E-Truncated cone	1.95	0.0651	1
F-Water-injection	-3.8	0.0335	1

*Water-injection cyclone (Box-Benkhen design)*

Based on the results of Plackett-Burman design, the following variables were used for the Box-Benkhen design.

Vortex finder diameter (0.75 in – 1.25 in)

Feed pressure ( 10 psi to 30 psi)

Water injection rate (5 gpm to 20 gpm)

The truncated cone diameter (TCD) and spigot diameter were kept constant at 1.0 in and 0.75 in respectively. During the experimentation it was observed that a large fraction of the coarse fraction was reporting to the overflow of the cyclone. This may be due to the higher water injection rate (20 gpm), which forces the particles to the overflow. The maximum value of the water injection rate was chosen based on the Plackett-Burman design, to study the effect of water injection rate in the region of 5 gpm to 20 gpm. Another reason may be due the relation between vortex finder diameter (VFD) and truncated cone diameter. As the truncated cone diameter was fixed at 1.0 in, use of a large vortex finder diameter may be causing disturbance in the flow pattern. Because of larger vortex finder diameter and a fixed truncated cone along with higher water injection

rate may cause the coarser fraction to report to the overflow. Hence, this study shows that the ratio of vortex finder diameter and truncated cone diameter is very important for classification in water injection cyclone. Since truncated cones of other diameters are not manufactured, further experiments were carried out maintaining vortex finder diameter and truncated cone diameter ratio of one, while varying the water injection rate. The VFD/TCD ratio of one was chosen based on the fact that to have a proper air core formation between vortex finder and spigot. The parameters and their levels are shown in Table 12.

Table 12. The parameters and their levels for water-injection cyclone (American coal)

Vortex finder diameter (in)	Truncated cone diameter (in)	Water injection rate (gpm)			
		5	8	11	14
0.75	0.75	5	8	11	14
1.0	1.0	5	8	11	14

The partition numbers generated are given in Table 13. It is clear from the table that increasing water injection rate decreases the -325 mesh fraction in the cyclone underflow. However, as the water injection rate increases, the percentage of coarser fraction reporting to overflow also increases. It is interesting to note that there is a sudden transition in the partition numbers while using a VFD and VCD of 0.75 in compared to the one using diameters of 1.0 in. The partition numbers in the latter case vary smoothly with increase in water injection rate. This probably is due the volumetric flow rate that can be handled at a given combination of VFD and TCD. A larger VFD and TCD can handle higher flow rates without affecting the flow pattern inside the cyclone. Whereas, a smaller VFD and TCD could not handle higher water flow rates, thus the excess water forces through the TCD giving rise to a sudden jump in the partition numbers. Higher water injection rates should be avoided as it disturbs the flow pattern, thus affecting the classification process.

The comparison of partition curves (actual) for with and without water injection cyclone is given in Figure 4. The  $D_{95}$  values are 75 and 45 microns respectively for with and without water injection. The percentage of -500 mesh and -325 mesh fractions reporting to underflow is 24% and 80% respectively in case of with water injection, where as it is 40% and 92% respectively in case of without water injection. The water injection slightly increases the cut point, while reducing the percent of fines in the underflow. This study clearly shows that the water injection at the apex of the cyclone reduces the fines content in the underflow.

Table 13. Partition numbers (uncorrected) for water-injection cyclone varying water injection rate at a constant VFD / TCD ratio. (American coal)

Size (mesh)	VFD= 0.75, TCD = 0.75				VFD= 1.0, TCD = 1.0			
	Water injection rate (gpm)				Water injection rate (gpm)			
	5	8	11	14	5	8	11	14
+16	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
16x30	100.0	100.0	100.0	42.4	100.0	100.0	100.0	91.5
30x50	100.0	100.0	100.0	26.0	100.0	98.8	98.4	93.4
50x70	100.0	100.0	95.3	18.0	100.0	98.0	97.7	88.6
70x100	100.0	79.1	64.1	18.0	98.6	96.6	97.5	84.8
100x200	94.5	67.4	56.1	24.5	96.6	93.5	94.1	86.2
200x325	87.7	67.4	55.8	28.3	91.4	88.3	92.0	83.2
325x400	83.3	63.5	51.9	25.2	81.4	77.6	80.0	78.3
400x500	76.7	47.7	38.8	18.1	74.0	71.2	77.6	70.5
-500	32.1	12.8	12.9	22.8	38.1	32.1	24.0	24.9

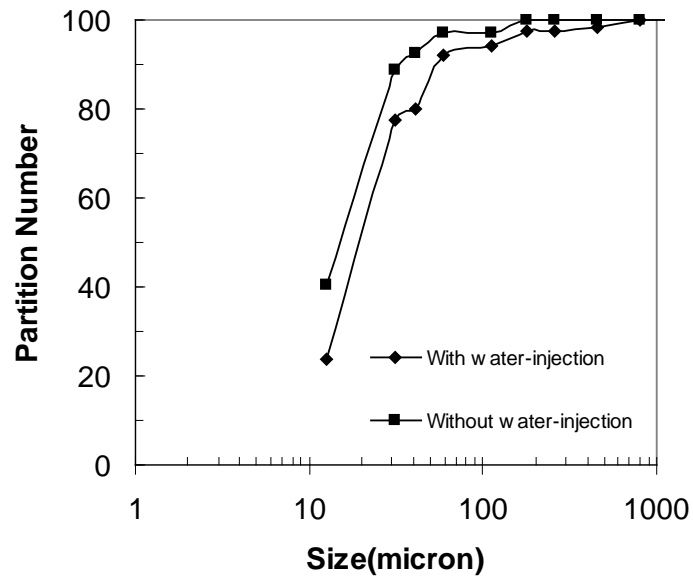


Figure 4. Comparison of partition numbers (actual) with and without water injection to cyclone. (American Coal)

### Experiments on Dense Medium Falcon Concentrator

The aim of this task was to quantify the effects of the operating parameters associated with the dense medium-based Falcon using a statistically designed experimental program on one of the coal slurry samples using the following operating parameters.

- Feed flow rate,
- Feed medium density,
- Bowl speed,

- Tailings underflow rate

The study (DOE project) recently completed on the heavy medium Falcon treating refuse pond coals showed that speed, underflow rate and medium density significantly affect the product ash. The lip width does not have much effect on product ash. An increase in bowl speed decreases the product ash content, which is likely due to the increase in particle settling kinetics. An increase in medium density resulted in a relatively sharp decline in product quality. The same affect was observed by decreasing the bowl speed below 20 hz, which is likely due to a drop in the settling kinetics of the high-ash content, near gravity particles. An increase in underflow rate generally decreases the product ash content with a reduction in product yield. Dr. R.Q. Honaker made similar observations while treating Illinois coal samples (ICCI project 97 – 1/2.1 A-1). The sink-float analysis of the Jader and American coals reveals that at a medium density of 1.55, the product yield is about 90% having ash content of 5% to 6%. A further increase in medium density does not have much effect on product yield and ash contents. Hence, variation of medium density in the Box-Benkhen design program may not affect the product yield and ash contents. The study conducted by Dr. R.Q. Honaker (ICCI project 97 – 1/2.1 A-1) showed that the dense medium Falcon concentrator operating under slightly higher medium density is capable of producing different specific gravity cuts by controlling the underflow rate of the Falcon concentrator. Hence, it was decided to use a constant medium density of 1.55. The following operating parameters were used for the Box-Benkhen design tests of American coal.

- Feed ash (7% – 20%)
- Bowl speed, (20 – 40 Hz)
- Tailings underflow rate (3 lpm – 15 lpm)

A total number of 17 experiments were performed using the Box-Behnken design. The samples collected from each experiment were wet screened through a 325-mesh sieve to separate the magnetite. A hand magnet removed the remaining magnetite. The +325 fractions were dried and analyzed for ash and total sulfur contents. The experimental conditions and responses are provided in Table 14.

The data were analyzed using the Design Expert software. Quadratic models were fitted to the data to understand the significance of each parameter and their interactions. The model equations relating the parameters and their interactions for responses product ash (%) and product yield (%) can be written in coded form as:

$$\text{Product Ash (\%)} = 8.26 + 2.22 \times A + 0.86 \times B - 1.18 \times C + 0.76 \times C^2 + 1.21 \times A \times B - 0.96 \times A \times C \quad [4]$$

$$\text{Product Yield (\%)} = 92.66 - 7.98 \times A + 1.04 \times B - 1.64 \times C - 2.62 \times A^2 + 1.88 \times C^2 - 2.61 \times A \times C \quad [5]$$

in which *A* is the feed ash (%), *B* the bowl speed (Hz) and *C* the underflow rate (lpm).



Table 14. The test design matrix and responses for the Box–Benkhen test program conducted on the dense-medium Falcon process using the American coal.

Run No.	Feed Ash (%) A	Bowl Speed (Hz.) B	Underflow Rate (lpm) C	Product Ash (%)	Product Yield (%)
1	13	40	3	11.23	96.81
2	8	40	9	6.32	99.03
3	18	30	3	12.97	90.11
4	13	20	3	10.23	93.56
5	13	30	9	7.69	93.37
6	13	30	9	8.93	92.93
7	18	20	9	8.12	79.48
8	8	20	9	6.34	99.00
9	13	30	9	7.32	91.31
10	18	40	9	12.92	82.88
11	8	30	3	6.34	98.96
12	18	30	15	8.99	79.52
13	13	40	15	8.64	94.84
14	13	30	9	8.21	92.93
15	13	20	15	7.53	93.17
16	13	30	9	8.51	92.51
17	8	30	15	6.21	98.81

The  $R^2$  values for the predicted and actual responses for product ash and yield were 0.94 and 0.96 respectively. The effects of the operating parameters on each response variable are summarized in the perturbation plots (Figure 5). As expected feed ash and underflow rate have the greatest effect on product ash content. The curvilinear nature of the product ash curve suggests that the product ash is a strong quadratic function of underflow rate, which is supported by a relatively low t-statistic obtained for  $C^2$  term. The increase in feed ash increases the product ash with decrease in yield. An increase in feed ash content from 12.77% to 18.44% increased the product ash from about 8% to 10.5% with a decrease in yield from about 92% to 82%. Hence, the change in feed properties significantly affects the process performance. Therefore, it is necessary to automate the dense-medium Falcon to maximize the product yield for a given product ash content for varying feed properties. The higher bowl speed increases the centrifugal force, thus providing accumulation of magnetite particle near the wall of bowl. This process increases the specific gravity of cut increasing the product ash and with a marginal increase in yield.

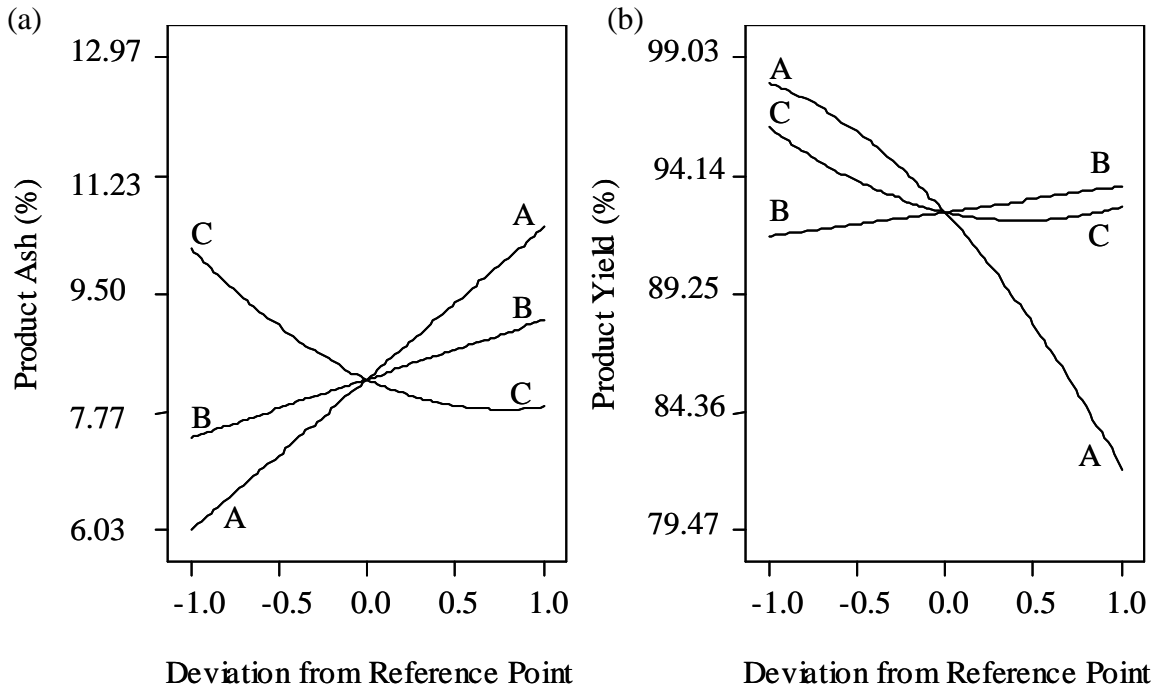


Figure 5. Perturbation plots showing the parameter effects on (a) product ash and (b) product yield. (American coal)

#### *Pyritic Sulfur Rejection Evaluation.*

Past studies on the water-only and dense-medium Falcon concentrators have indicated that the water-only Falcon concentrator can achieve low  $E_p$  values at low gravity cut points for treating the +200 mesh particle size fraction, thus achieving a very efficient separation performance in terms of ash rejection. As a result of the higher inertia of similar sized coal pyrite particles in comparison with the ash forming mineral matter particles, efficient separation in terms of pyrite rejection has been observed down to the 325 mesh particle size range. Similar results have been observed for the dense-medium Falcon, although at a significantly higher separation efficiency levels.

To study the performance of the dense-medium Falcon concentrator for pyrite rejection, tests were conducted on the Jader refuse sample, which contained 6.3% pyritic sulfur. Tests were not conducted on the Jader cyclone feed or the American coal samples as they contained relatively low sulfur contents of 4.0% and 2.6% respectively. The Jader refuse sample contained 48.8% ash. The washability characteristics of this sample are presented in Table 15.

A series of tests were conducted treating this sample using the dense-medium Falcon concentrator varying the medium density, bowl speed and the underflow rate over a range of 1.4-1.5 g/cc, 20-25 Hz and 10-19 lit/min respectively. The ash rejection performance achieved in these tests is shown in comparison to the washability characteristics of this sample in figure 6 (a). Three tests were selected from this series of tests for further

investigation with respect to the pyritic sulfur rejection performance. These tests corresponded with 1.4 g/cc media density, 15% solids content, 20 Hz bowl speed and 16, 13 and 19 lit/min underflow rates. The feed, product and tailings samples associated with these three tests were assayed for pyritic sulfur content. It was found that at product pyritic sulfur contents of 1.31%, 2.72% and 2.02% a pyrite rejection of 96.45%, 83.00% and 88.54% was achieved. These results are shown in comparison to the washability performance of this sample in figure 6 (b).

Table 15. Washability data for -16 x 325 mesh Jader refuse coal

Specific gravity fraction	Individual			Cumulative			
	Weight (%)	Ash (%)	Pyritic Sulfur (%)	Weight (%)	Ash (%)	Pyritic Sulfur (%)	Combustible Recovery (%)
1.3	20.49	3.77	1.02	20.49	3.77	1.02	38.53
1.3X1.4	8.11	7.85	1.14	28.60	4.92	1.05	53.14
1.4X1.5	5.07	15.60	3.07	33.67	6.53	1.36	61.50
1.5X1.6	3.65	27.59	5.07	37.32	8.59	1.72	66.67
1.6X1.7	2.84	29.51	5.76	40.16	10.07	2.01	70.58
1.7X1.8	3.85	30.24	7.87	44.02	11.84	2.52	75.83
1.8X2.1	8.11	47.08	9.03	52.13	17.32	3.53	84.22
2.1	47.87	83.13	9.32	100.00	48.83	6.30	100.00
Total	100.00	48.83	6.30				

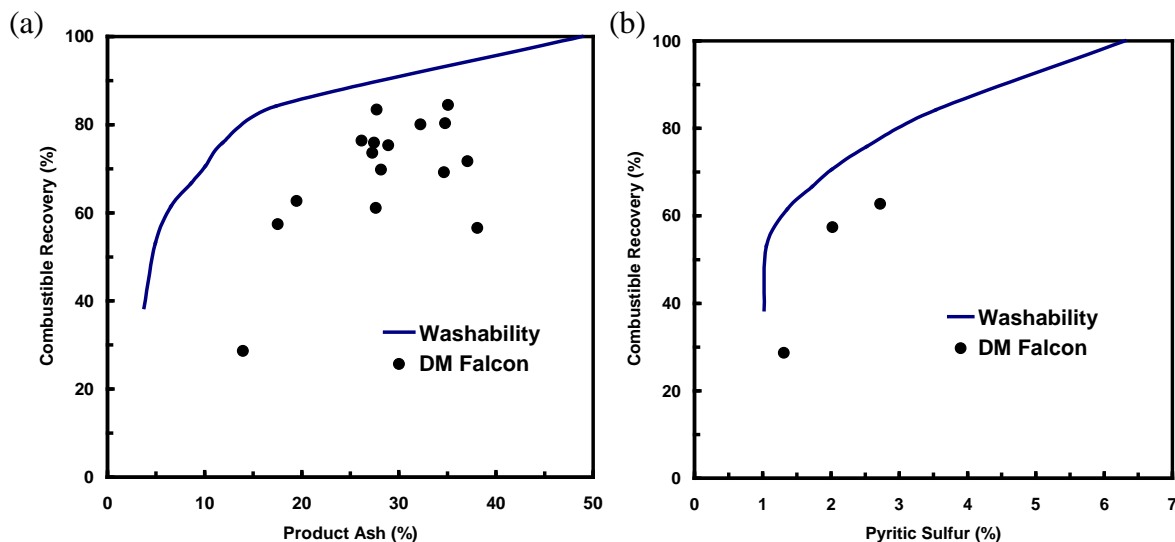


Figure 6. Separation performance achieved from the treatment of the 16 x 325 mesh size fraction of the Jader refuse coal with respect to (a) ash rejection and (b) pyritic sulfur rejection.

It can clearly be seen from figure 6 (b) that excellent pyrite rejection performance was achieved. By comparing figures 6 (a) and (b), it can be seen that the test results for pyritic sulfur are much closer to the washability curve compared to the test results for ash. This indicates that the pyrite rejection performance of the dense-medium Falcon concentrator is superior to its ash rejection performance.

### Tests with Eriez magnetic separator

Tests were conducted based on a two level factorial design of experiments, varying applied voltage, feed rate and feed percent solids to evaluate the influence of these operating conditions on the magnetic separation achieved. Tests were also conducted varying the magnetite content to simulate scavenger and cleaner circuits. A total of 15 experiments were conducted as listed in Table 16. The magnetite loss was used as the response and was calculated from the magnetite contents of the magnetic and nonmagnetic streams.

Table 16. The experimental design matrix and magnetite loss response obtained from magnetic separation evaluation.

Test No.	Field Strength (Volts)	Flow Rate (gpm)	Pulp Density (g/cc)	Magnetite Loading (%)	Magnetite Loss (lb/ton)
1	99.00	2.00	1.42	28.98	91.0
2	99.00	8.00	1.42	28.98	119.1
3	77.00	8.00	1.20	13.94	132.6
4	77.00	2.00	1.42	28.98	86.3
5	88.00	5.00	1.31	22.10	49.4
6	99.00	8.00	1.20	13.94	50.6
7	77.00	8.00	1.42	28.98	184.3
8	99.00	2.00	1.20	13.94	46.0
9	88.00	5.00	1.31	22.10	37.8
10	77.00	2.00	1.20	13.94	132.6
11	88.00	5.28	1.22	11.15	49.3
12	99.00	5.28	1.22	11.15	34.4
13	88.00	5.59	1.36	20.59	85.9
14	99.00	5.59	1.36	20.59	62.8
15*	99.00	2.00	1.12	1.90	2.9

\* Scavenger Operation

It is apparent from Table 16 that experiments 1 through 14, which were single stage operations, failed to achieve a satisfactory separation performance. Test 15, which was a rougher-scavenger operation provided good separation performance as is evident from the low magnetite loss of only 2.9 lb/ton.

Though the experimental design tests (Tests 1-10), could not achieve an acceptable separation performance, did provide support for the directional response expectations of the operating condition variables. Figure 7 (a) shows that increase in magnetic intensity resulted in better performance as characterized by lower level of magnetite loss. Similarly, a lower flow rate resulted in better performance due to allowance of a higher residence time for the feed slurry in the separator. Figure 7 (b) indicates that magnetite losses of close to zero at high field intensities and low magnetic loading of the feed. In a rougher-scavenger operation, the scavenger feed will indeed have a low magnetic loading, and, when subjected to high field intensity, will be able to produce a satisfactory level of separation performance. This is evidenced from the results obtained for Test 15. At a magnetite loading of 1.9%, a low magnetite loss of 2.9 lbs/ton was achieved at a field intensity of 99 Volts, which corresponds to approximately 1200 gauss.

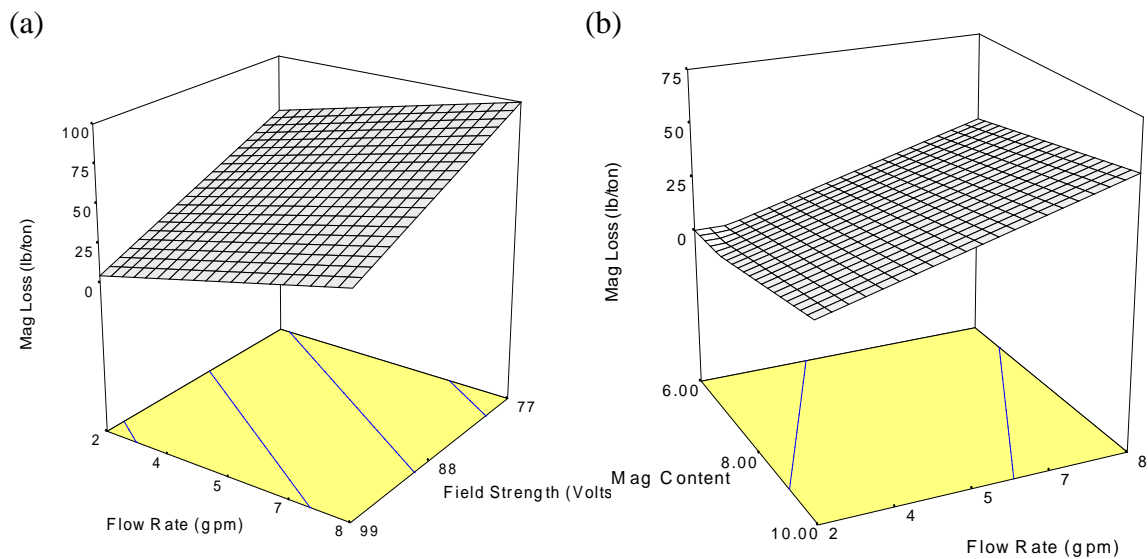


Figure 7. (a) & (b) Influence of feed flow rate, magnetic intensity and magnetite loading on separation performance.

### Process Automation and Control

The aim of this task was to develop a control strategy for the Falcon Concentrator, using an on-line coal slurry analyzer to adjust its operating parameters suitably to varying feed characteristics.

#### *Conceptual design of control strategy.*

The AMDEL Coal Slurry Analyzer (CSA) unit, provides the ash content and percent solids of the appropriate slurry stream, which is the clean coal and feed streams in the case of methods 1 and 2, respectively. It is incorporated with a signal analyzer, so that the parameters of the Falcon concentrator can be controlled. An indirect control strategy, using feed characteristics information to control the product characteristics was chosen for evaluation in this study.

The control algorithm will be as below:

1. Collect the feed and solids ratio data from AMDEL.
2. Perform an optimization procedure to identify the required bowl speed and underflow rate to maintain a given product grade given the developed empirical models.
3. Set the bowl speed and underflow rate.
4. Go to step 1.

*Experimental design for optimization model development.*

Implementation of the control strategy requires a model relating the operating variables to the response variables. Such a model was developed using statistical techniques. The details of this model have been discussed in previous sections. These developed empirical relations provide the degree of effect of individual variables and their interactions (Eqs. 4 and 5). These empirical relationships allow the determination of the optimum parameter values providing maximum yield over a range of ash contents.

*Implementation of optimization routines.*

A Levenberg-Marquardt gradient search algorithm was implemented to perform a constrained optimization routine which identifies the operating conditions (Bowl speed and underflow rate) that will provide the maximum combustible recovery for any given product quality constraints.

*Hardware and software setup.*

The hardware and software setup was accomplished for testing the control strategy. The Coal slurry Analyzer (CSA) measures and transmits raw count rates to a computer. The calibration equations programmed into the computer convert the raw count rates to actual ash content and solids ratio values after applying proper corrections for temperature effect. The computer connected to the CSA transmits the ash content and solids ratio data in real-time whenever polled by another master modbus protocol computer. The master computer hosts the optimization routines and consists controller software to manipulate bowl speed and the underflow rate. The ash content and solids ratio data from the slave computer is fit into the empirical models developed from the statistical experimental designs. The optimization routine calculates the required operating parameter settings to achieve the desired product quality. The optimal bowl speed setting is directly controlled by the computer while the underflow rate adjustment is displayed for manual adjustment.

*Difficulties in implementing automatic control of underflow rate.*

A problem regarding control of underflow flow rate was observed. Adjusting the pneumatic control valve setting controls the underflow of the Falcon concentrator. The setting is manipulated using varying levels of air pressure. Thus the control strategy manipulates the air pressure (measured variable) to achieve underflow rate control.

However, it was observed that particular settings of air pressure did not have a repeatable correspondence with the actual underflow rate achieved. This is because the underflow rate is not only a function of the air pressure (and thus the underflow valve opening) but is also dependent on the rate of pressure buildup. The rate of pressure buildup influences the bed buildup inside the rotating bowl of the falcon concentrator and thus affects the underflow rate.

To overcome this problem, an underflow rate meter can be installed. This will allow direct measurement of the underflow rate. Upon the knowledge of the underflow rate, the air pressure settings can then be iteratively adjusted using a PID control loop to converge at the desired flow rate setting.

Availability of a suitable underflow rate meter was an issue due to the very high solids content, low flow rate and presence of magnetite in this stream. Thus, a manual control for manipulation of this operating parameter was used while providing recommendations for implementing an automatic control. The suggested underflow rate control strategy however needs to be evaluated for stability and quickness of response.

#### *Automation and Control Testing*

A series of eight tests was conducted varying the feed ash content to the Falcon concentrator in course of operation. Target product ash content was also varied in the middle of operation. Samples were collected from the feed, product and reject streams and were analyzed for actual ash content determination and actual yield calculation. The list of the eight experiments along with the observed ash contents and mass yields is presented in Table 17.

Table 17. Automation and Control strategy testing. Feed percent solids maintained constant at 15%. Density cut point maintained constant at 1.5.

Test No.	Approx. Measured Feed Ash (%)	Product Target Ash (%)	Bowl Speed Setting (Hz)	U-Flow Rate Setting (lpm)	Actual Feed Ash (%)	Actual Product Ash (%)	Actual Reject Ash (%)	Actual Yield (%)	Predicted Yield (%)
1	13	10	27.77	3.0	13.31	10.42	64.35	94.66	95.94
2	14	10	22.47	3.0	14.49	10.57	65.32	92.82	94.2
3	15	10	20.0	3.24	15.12	10.49	66.21	91.73	92.3
4	15	12	33.97	3.0	15.19	11.63	68.34	93.70	94.02
5	17	12	25.94	3.0	16.80	12.28	62.35	90.97	89.77
6	19	12	21.26	3.0	19.32	12.42	63.42	86.51	85.04
7	22	12	20	4.26	22.40	12.67	55.24	77.14	74.93
8	25	12	20	5.69	25.81	12.55	51.24	65.75	62.3

It can be seen from Table 17 that the actual feed ash content and the measured feed ash contents are approximately the same. This indicates a sufficient accuracy of measurement from the CSA. The target ash content was also consistently achieved as seen from the correspondence of the target ash values to the measured ash contents. It is to be noted however, that the actual measured product ash contents were consistently higher by approximately 0.5% than the target setting. This discrepancy, though minor, could be a result of an offset in the ash prediction model. The actual and predicted yields show an excellent match with each other indicating a good implementation of the control strategy. A closer look however indicates that the correspondence is better at higher mass yield values compared to lower mass yield values. This observation along with the excellent fit of the actual and predicted mass yield values could be a result of the fact that at high mass yields, the tailings ash content does not have a major bearing on the mass yield.

Overall, the results indicate that the control strategy was successful in controlling the Falcon concentrator operation for achieving optimum separation performance even in the presence of fluctuating feed characteristics.

## CONCLUSIONS AND RECOMMENDATIONS

### Conclusions

- The Jader and American coals contain about 19% and 29% ash having 4% and 2% total sulfur respectively.
- The washability tests of Jader and American coals show that even though these coal can be classified as an easy to clean coal, a high percent of material (35%) below 48-mesh indicates that it is essential to use an enhanced gravity technique to achieve the required combustible recovery.
- The Amdel ash analyzer was installed and calibration equations were developed for different range of ash values.
- The most important parameters for water-injection cyclone are vortex finder diameter, water-injection rate and spigot diameter for both coals. The percent solids does not have significant effect on the classification.
- The truncated cone of water-injection cyclone is a significant parameter for Jader coal at 95% confidence level. Where as for American coal the cone is a significant parameter at 90% confidence level. The feed pressure significantly affects the classification of Jader coal, where as for American coal it does not have much effect.
- The hydrocyclone experiments without water injection show that, for cut point ( $D_{95}$ ) the most important parameters are vortex finder diameter and percent solids. The percent solids also affect the cut point, which increases with increase in percent solids.
- The ratio of vortex finder diameter to truncated cone diameter is very important. A ratio higher than one affects the classification process. It is good to have a ratio of one or less than one to provide proper formation of air core inside the cyclone.



- The  $D_{95}$  values are 75 microns (200 mesh) and 45 microns (325 mesh) respectively for with and without water injection. The percentage of  $-500$  mesh and  $-325$  mesh fractions reporting to underflow is 24% and 80% respectively in case of with water injection, where as it is 40% and 92% in case of without water injection.
- The water injection slightly increases the cut point, while reducing the percent of fines in the underflow. This study clearly shows that the water injection at the apex of the cyclone reduces the fines content in the underflow.
- The dense medium Falcon experiments show that the feed ash and underflow rate have the greatest effect on the product ash content. The product ash is a strong quadratic function of underflow rate.
- The increase in feed ash increases the product ash, reducing the product yield. An increase in feed ash content from 12.77% to 18.44% increased the product ash from about 8% to 10.5% with a decrease in yield from about 92 % to 82%.
- Tests on the Jader refuse sample indicate that an excellent pyritic sulfur rejection performance was achieved using the dense-medium Falcon concentrator. A product containing 2.62% pyritic sulfur was produced from a feed pyritic sulfur content of 6.30% at a combustible recovery of 62.69%. Lowest product pyritic sulfur content of 1.31% was also achieved from this high pyritic sulfur content feed.
- Magnetite recovery tests on the dense medium Falcon concentrator product indicate that a rougher-scavenger arrangement is essential to achieve low levels of magnetite losses. Tests on such an arrangement at high magnetic intensity resulted in a relatively low magnetite loss of 2.9 lbs/ton.
- Effectiveness of single stage recovery circuit has been demonstrated by University of Kentucky researchers for a similar setting. This study however does not confirm those findings. Further investigation might be necessary to resolve the discrepancy.
- A search algorithm has been implemented to perform a constrained optimization routine, which identifies the operating conditions that will provide the maximum combustible recovery for any given product quality constraints.
- Difficulties were encountered in the measurement and control of the underflow rate. The flow measurement problem was due to the extremely high solids content of this stream which also contains magnetite. Difficulty in implementing the flow rate control on this stream was faced due to the seeming lack of correlation between the underflow rate and the air pressure used to change the flow rate. In light of these difficulties, a semi-automatic control was established in which online optimization of the underflow rate was achieved but the setting was accomplished manually. The bowl speed optimization and control was setup in a completely automatic loop.
- The automation and control strategy testing results indicate that the control strategy was successful in maintaining optimum separation efficiency of the Falcon concentrator in the presence of fluctuating feed characteristics.
- The product ash content and mass yield predictions of the optimization model were also realized.

## Recommendations

Recommendations for future work will include:

- Development of proper underflow rate control system for the Falcon concentrator.
- Design of new method for the removal of tailings from the Falcon concentrator.
- Necessary to study the formation and behavior of particle bed inside the Falcon.
- Further improvements in magnetite recovery are desired to lower the magnetite losses as well as to reduce the capital requirements by elimination of the two stage circuits.
- An indirect control strategy using feed quality information to control the product quality has been used in this study. It has to be noted however that a better control strategy would utilize the simultaneous analysis of both the product and reject streams.

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