Project Title: PRODUCTION OF ILLINOIS BASE COMPLIANCE COAL USING ENHANCED GRAVITY SEPARATION

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ABSTRACT

Phase I compliance coal was produced from all Illinois Basin coal samples in this project using both the Falcon and Knelson Concentrators. Tests conducted under optimum conditions produced coal around 2 lbs SO₂/MBTU with over 90% combustible recovery from feeds as high as 20% ash and 7 lbs SO₂/MBTU sulfur. The samples, which contained relatively low amounts of organic sulfur (~1%), were directly obtained from Illinois coal preparation plants and did not involve further grinding. Units rated for 50 to 150 tons/hour with operating costs estimated at 40 cents per ton of coal are commercially available, and provide sulfur reductions well under the current price of SO₂ emission allowances. Toxic trace elements such as lead and cadmium were almost completely removed with other elements responding as if associated with the non-pyritic ash and organic phases.

The Falcon concentrator was found to be more effective at treating the 65 x 400 mesh size fraction while the Knelson unit was more effective for the +65 mesh size fraction. The Falcon concentrator was found to achieve efficient separations at relatively low gravity-cut points between 1.5 and 1.7. Bowl geometry was found to be critical for establishing the separation performance of the Falcon unit.
EXECUTIVE SUMMARY

Illinois Basin coals usually contain a significant portion finely dispersed pyrite. With Phase I of the Clean Air Act becoming effective in 1995, Illinois coal producers will need to produce a lower sulfur product to avoid loss of market. Physical coal cleaning can, in theory, remove pyritic sulfur from Illinois coals. In some cases, this will be sufficient in producing a marketable coal that meets the maximum Clean Air Act sulfur dioxide emission limits.

At coarse coal particle sizes (+28 mesh), most of the pyrite is not sufficiently liberated from the coal matrix. Thus, physical cleaning in many current preparation plants cannot remove enough pyrite to ensure compliance. Therefore, to achieve effective pyrite rejection, the coal particle size must be reduced to a very fine size, typically less than 28 mesh. Froth flotation is the process most commonly used to treat this fine fraction. The process, however, has poor selectivity with respect to middling particles. For example, a particle covered by 90% pyrite and 10% coal may have enough coal surface area for bubble attachment and flotation. On the other hand, the same particle would be rejected easily by a gravity-based process due to the large density differences between coal and pyrite. Unfortunately, in the past, gravity-based separators have been ineffective at treating fine particles due to the low particle inertia.

One way of achieving a gravity-based separation on fine particles is to exert an enhanced gravity force on these particles using a centrifugal action. Both the Falcon Concentrators Incorporated and Knelson Gold Concentrators Incorporated have developed large commercial gravity separators for the gold and metal mining industries based on this principal. These units are capable of operating continuously with throughputs of up to 200 tph. Because manufacturers already have units sufficiently large for the fine circuits at most Illinois preparation plants, there would be no delay in creating large commercial units from small laboratory proto-types.

The current project evaluated the Falcon and Knelson continuous commercial units for their ability to remove pyritic sulfur from fine coal streams. The units were also tested for their ability to de-ash fine coal. The specific objectives of the project were (1) to demonstrate the use of
enhanced gravity concentrators for the efficient and economical treatment of fine coal, (2) to identify and optimize the critical operating parameters of the Falcon and Knelson centrifugal units, (3) to evaluate and compare the throughput capacity and scale-up factors of both units and (4) to determine the effect of the applied centrifugal field on the gravity cut point and process efficiencies.

To achieve the project objectives, the operating parameter values for the Falcon and Knelson concentrators were tested over a large range of values to determine their effects on process performance and to establish their respective limiting values. The response variables included total and pyritic sulfur rejection, ash rejection, BTU recovery, and separation efficiency. These tests involved the treatment of a -28 mesh coal sample and a flotation concentrate from an Illinois Basin coal preparation plant. Optimization of the operating variables was achieved using data collected from tests performed in a statistically-designed experimental program.

Using the optimized parameter values, additional tests were conducted on the both the Knelson and the Falcon concentrators to evaluate the effect of volumetric flow rate and centrifugal force on separation performance. The Falcon concentrator was found to be very effective for treating the 28 x 400 mesh size range over a volumetric flow rates of 10 to 40 gpm at a feed solids content of 16% by weight. These flow rates correspond to mass flow rates of 0.5 to 2.0 tph. The Knelson concentrator was effective at treating flow rates up to 10 gpm at a solids content of 30% which corresponds to a mass flow of nearly 1 tph. Increasing the mass flow rate resulted in a 20% decrease in separation efficiency.

Partition curves revealed that the Falcon concentrator has the ability to achieve relatively low gravity cuts ($D_{50}$) ranging from 1.5 to 1.7 for the 65 x 400 size fraction. The $D_{50}$ values obtained for the coarser +65 mesh size fraction ranged from 1.7 to 2.0. Bowl geometry was found to be critical for determining the separation performance of the Falcon Concentrator. The magnitude of the applied centrifugal force was found to effect the $D_{50}$ value achieved by the use of a long bowl. A low gravity cut point of 1.5 was achieved by increasing the g-force to 200g. However, this effect was not realized for the short bowl. The $D_{50}$
value and the $E_p$ value remained relatively unchanged over a g-force range of 70g to 200g with only a slight decrease in efficiency realized with a g-force of 70.

The separation efficiency achieved by the Falcon Concentrator for the treatment of the 65 x 400 mesh size fraction was excellent. The $E_p$ values achieved for this fraction ranged from 0.10 to 0.15. However, treatment of the +65 mesh size fraction was less efficient as indicated by $E_p$ values ranging from 0.25 to 0.40.

Both the enhanced gravity concentrators were successful at producing Phase I compliance coal from all feed streams tested. Success was achieved on coals with varying degrees of prior processing, ranging from untreated fines circuit feed to flotation circuit feed. Compliance coal was produced from low-to-high ash content coals. The feed total sulfur contents ranged from 1.3% to 4.0%, with the organic sulfur content being nearly 1% for all the coal samples tested. For the high sulfur content coal sample, the total sulfur content was reduced to 1.4% which was a result of high pyritic sulfur rejections ranging from 80% - 98%. An 85% rejection of pyritic sulfur at a combustible recovery of 85% was found to be achievable for both the Falcon and Knelson concentrators.

Ash-forming material was found to be substantially rejected in the 28 x 400 mesh size fraction by both concentrators. At 2.1 tph, the ash content of the 100 x 325 fraction in an Illinois No. 5 coal sample was reduced from 18% to 8% using the Falcon Concentrator with a high combustible recovery of 97%. Both concentrators, however, were found to be ineffective at treating the -400 mesh size fraction.

The performance of enhanced gravity concentration in trace element reduction depends on the association of the trace element. Toxics, such as cadmium and lead which have an affinity for pyrite in the samples tested, were almost totally eliminated. Other toxic elements, such as arsenic that appear to have an organic and ash affinity, were removed only to the extent that the coal was de-ashed. Toxics, such as chromium, that appear to be highly organically linked, were not rejected by the gravity concentrators.
PROJECT OBJECTIVES

The overall goal of this project is to provide the Illinois Basin coal industry with a means of reducing sulfur in the fine coal streams in time to assist with the Phase I requirements of the Clean Air Act. To accomplish this goal, the project investigated enhanced gravity concentrators that have already been developed to the size required for installation into coal preparation plants. These concentrators have known capital and operating costs and space requirements that would allow installation into existing preparation facilities. These enhanced gravity concentrators, i.e., continuous Falcon and Knelson Concentrators, have not been tested and proven for coal. To demonstrate the application of these concentrators for the treatment of Illinois Basin coal fines, the project objectives are:

1. To demonstrate the use of enhanced gravity concentrators for the efficient and economical treatment of fine coal,
2. To identify and optimize the critical operating parameters of the Falcon and Knelson centrifugal units,
3. To evaluate and compare the throughput capacity and scale-up factors of both units,
4. To determine the effect of the applied centrifugal field on the gravity cut point and process efficiencies, and
5. To evaluate the potential application of enhanced gravity separators to reduce toxic trace elements found in run-of-mine coal.

INTRODUCTION

Illinois Basin coals usually contain a significant portion of finely dispersed pyrite. With Phase I of the Clean Air Act becoming effective in 1995, Illinois coal producers will need to produce a lower sulfur product to avoid loss of market. Physical coal cleaning can, in theory, remove pyritic sulfur from Illinois coals. In some cases, this will be sufficient in producing a marketable coal that meets the maximum Clean Air Act sulfur dioxide emission limits.
At coarse coal particle sizes (+28 mesh), most of the pyrite is not sufficiently liberated from the coal matrix. Thus, physical cleaning in many current preparation plants cannot economically remove enough pyrite to ensure compliance. Therefore, to achieve effective pyrite rejection, the coal particle size must be reduced to a very fine size, typically less than 28 mesh. Froth flotation is the process most commonly used to treat this fine fraction. The process, however, has poor selectivity with respect to middling particles. For example, a particle covered by 90% pyrite and 10% coal may have enough coal surface area for bubble attachment and flotation. On the other hand, the same particle would be rejected easily by a gravity-based process due to the large density differences between coal and pyrite. Unfortunately, in the past, conventional gravity-based separators have been ineffective at treating fine particles due to the low particle inertia.

One way of achieving a gravity-based separation on fine particles is to exert an enhanced gravity force on these particles using a centrifugal action (Han and Say, 1985). The enhanced gravity concentrators that operate continuously and are commercially available include the Multi-Gravity Concentrator (MGS), the Kelsey Jig, the Knelson Concentrator, and the Falcon Concentrator. Both the Falcon and Knelson Concentrators have been commonly used in the gold and metal mining industries to treat mass flow rates up to 200 tph in a single unit.

Initial studies using enhanced gravity separators for fine coal cleaning combined advanced froth flotation with the MGS unit for improved sulfur rejection (Luttrell et al., 1993). However, tests performed on the Kelsey Jig found that high ash rejections can also be achieved on fine coal using enhanced gravity separation (Riley and Firth, 1993). Work conducted at SIUC using a semi-batch Falcon concentrator also found that high ash and sulfur rejections can be achieved on the 28 mesh by 10 μm size fraction of a fine circuit feed coal stream (Honaker et al., 1994).

The use of centrifugal washers, if determined to be feasible, has near term application. The problem with applying these enhanced gravity separators to Illinois coal fines is that there is almost no test data for these units
operating on coal. Because manufactures already have units sufficiently large for the fine circuits at most Illinois preparation plants, there would be no delay in installing large commercial units based on test data produced from pilot-plant units.

EXPERIMENTAL PROCEDURE

Enhanced Gravity Concentrators

Falcon Concentrator: The Falcon concentrator used in this investigation measured 10-inches in diameter and had the ability to supply up to 300 g's of centrifugal force. The centrifugal force was used to cause deposition and stratification of the fine particles against the inside of a smooth centrifugal bowl. As shown in Figure 1, the feed is introduced at the bottom of the bowl and onto a spinning rotor. An impeller hurdles the feed against the wall of the rotor. The bottom of the rotor is called the migration zone, and is inclined at a slight angle so that the enhanced gravity field generated by the spinning rotor can be resolved into two force components. The strong component normal to the wall is the concentrating gravity field that provides the strong g-forces for the hindered settling processes and stratification of the feed. The weak driving component parallel to the inclined rotor surface pushes the stratified solids up toward the top of the bowl.

Figure 1. A schematic illustration of the operating principles of the continuous Falcon Concentrator.
The angle of incline on the rotor surface changes near the top of the rotor so that it is now parallel to the axis of rotation. As a result, there is no weak gravity force component to drive particles upward toward the top of the rotor. This part of the rotor is called the retention zone. Light particles on the outside of the bed move upward to the overflow lip of the rotor using the momentum they accumulated in the migration zone and the force of the upward flowing water film. Heavy particles and coarse, light particles form a bed on the bowl surface with the heavy particles forming a layer nearest the bowl wall. The bed of particles move along the bowl wall and across a 1/4-inch slot that exists around the circumference of the bowl. The heavies settle into the slot and are discharged through 1/8-inch nozzles. The light, coarse particles flow over top the slot and report to the overflow as the final product with the particles that remained dispersed in the feed water.

**Knelson Concentrator:** The main feature of the Knelson concentrator is that the particles are separated based on density in an active fluidized bed using 60 g's of centrifugal force. The Knelson unit used in this study had a 12-inch bowl diameter. As shown in Figure 2, a series of rings placed at equal distances apart along the vertical axis of the bowl wall entrap the heavy particles. The fluidized bed is maintained by injecting water at a rate of 25 gpm or more around the circumference of the bowl along

![Diagram](image)

**Figure 2.** A schematic illustration of the operating principles of the continuous Knelson Concentrator.
the bottom edge of each ring. After forming a solids bed behind the rings, the heavy particles are discharged using 1/4-inch nozzles. A pinch valve on each nozzle controls the rate of discharge. The light material travels over the rings and reports to the overflow as the final product.

Test Sample

The coal sample used in most of the tests in this study was collected from the fine circuit feed stream (28 mesh x 0) of a coal preparation plant treating the Illinois (Herrin) No. 5 seam coal. The original feed solids content of the stream was 18% by weight. A size-by-size analysis of the sample is provided in Table 1.

Table 1. The size-by-size characterization data obtained for the Illinois No. 5 fine coal slurry sample used in this study.

<table>
<thead>
<tr>
<th>Size (mesh)</th>
<th>Weight (%)</th>
<th>Ash (%)</th>
<th>T. Sulfur (%)</th>
<th>Pyritic Sul. (%)</th>
<th>BTU/lb</th>
</tr>
</thead>
<tbody>
<tr>
<td>+65</td>
<td>33.1</td>
<td>23.83</td>
<td>3.75</td>
<td>2.51</td>
<td>10,849</td>
</tr>
<tr>
<td>65 x 400</td>
<td>32.4</td>
<td>21.68</td>
<td>4.05</td>
<td>3.04</td>
<td>11,079</td>
</tr>
<tr>
<td>-400</td>
<td>34.5</td>
<td>64.75</td>
<td>1.64</td>
<td>1.26</td>
<td>4,600</td>
</tr>
</tbody>
</table>

The other coal samples tested in this study were also obtained directly from a coal slurry stream at an operating coal preparation plant. An Illinois No. 6 coal slurry sample was obtained from a conventional flotation feed stream. Another Illinois No. 5 coal slurry sample was collected from the spiral concentrator feed stream. Both samples were nominally -28 mesh.

Experimental Procedure

Prior to each test, 4 fifty-five gallon drums of coal slurry were placed in a feed sump where the feed solids content was adjusted to the desired value. During the tests, the Falcon unit was fed from a split stream on a recirculation loop that transported material from the bottom of the feed sump to its top. The feed rate was adjusted using valves located on the recirculation line. The Falcon unit was
mounted slightly above the feed sump so that the overflow (product) and underflow (tailings) streams could be gravity fed back into the feed sump. After allowing sufficient time for the process to reach steady-state, a timed-sample of the feed, product, and tailing streams were collected in short incremental time periods for approximately 5 minutes. The product and tailing samples were then wet screened into three size fractions, e.g., +65 mesh, 65 x 400 mesh, and -400 mesh.

Due to the requirement of fluidization water, the Knelson concentrator was operated closed-circuit using a Krebs 4-inch diameter hydrocyclone to bleed excess water from the feed stream. The hydrocyclone underflow was the feed to the Knelson while the cyclone overflow was discharged to a water treatment facility. The solids content of the cyclone feed was approximately 20% and the cyclone underflow or Knelson feed was about 30% by weight. The Knelson unit was also elevated to allow the underflow and overflow streams to report to the feed sump.

RESULTS AND DISCUSSION

Parametric Study

Falcon Concentrator: An experimental program based on a Box-Behnken statistical design was conducted on the Falcon Concentrator to evaluate the effect of the operating parameter values on separation performance. The parameters and their respective values studied in the Box-Behnken design, which required a total of 28 tests, are shown in Table 2. The overflow and underflow samples were screened to obtain size-by-size results. The test data, which resulted from the treatment of the -28 mesh Illinois No. 5 coal sample, were used to develop empirical relationships describing the response variables (i.e., separation efficiency and total sulfur rejection) as a function of the operating parameter values. A quadratic model was found to provide the best fit for the experimental data and took the following form:

\[ R.V. = k_1 + k_2(FR) + k_3(FS) + k_4(BS) + k_5(OT) + k_6(FR)^2 + \ldots + k_{15}(BS)(OT) \]  \[1\]
where R.V. is the response variable, FR the volumetric feed rate, FS the feed solids content, BS the bowl speed, OT the opening time of the underflow pinch valve which controls the underflow rate, and \( k_f \) the parameter constants. The closing time for the underflow valves was kept constant at 4 seconds throughout the 28 tests. The coefficient of determination or \( R^2 \)-value, which was used evaluate the closeness-of-fit, was greater than 0.90 for all models. The optimum parameter values, which are also shown in Table 2, were obtained on a size-by-size basis by determining the values corresponding to the predicted maximum separation efficiency. Separation efficiency was calculated by subtracting ash recovery to the product from combustible recovery. The maximum separation efficiency for the 28 x 100 mesh size fraction was predicted to be 40% while a value of 60% was estimated for the 100 x 325 mesh size fraction.

**Table 2.** A list of the operating parameters, the parameter value ranges studied in the Box-Behnken test program, and the optimum parameter values for the treatment of the 28 x 100 and 100 x 325 mesh size fractions.

<table>
<thead>
<tr>
<th>Operating Parameter</th>
<th>Parameter Value Range</th>
<th>Optimum Parameter Value (28 x 100 M)</th>
<th>Optimum Parameter Value (100 x 325 M)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feed Rate (gpm)</td>
<td>20 - 40</td>
<td>24</td>
<td>20</td>
</tr>
<tr>
<td>Feed Solids (%)</td>
<td>16 - 30</td>
<td>16</td>
<td>16</td>
</tr>
<tr>
<td>Opening Time (s)</td>
<td>0.5 - 1.5</td>
<td>1.3</td>
<td>1.0</td>
</tr>
<tr>
<td>Bowl Speed (hz.)</td>
<td>20 - 40</td>
<td>24</td>
<td>39</td>
</tr>
</tbody>
</table>

Comparing the optimum values in Table 2 obtained for the two size fractions, it is apparent that the optimum feed solids content is the same for both size fractions while the optimum values of the other parameters differ. A smaller volumetric feed rate is desirable for the 100 x 325 fraction most likely due to a need for additional retention time to allow the ash-forming particles to settle to the bowl wall. The higher bowl speed was also found to be desirable for the finer fraction which is probably a result of the need for a higher g-force to allow the mineral particles to report to the bowl wall within the given retention time. The longer optimum opening time for the 28 x 100 mesh size fraction is likely due to the slower optimum bowl speed. The
centrifugal force assists the discharge of the underflow material. Thus, to maintain a given underflow rate while decreasing bowl speed, the opening time must be increased.

Using the optimum parameter values, additional tests were conducted to study the effect of volumetric feed flow rate and the applied centrifugal field on separation performance for two different bowl geometries. The bowls differ in their slope with the steeper bowl having the longer body and, thus, the smaller upward moving force used to drive the heavies to the underflow slot. Figures 3(a) and 3(b) show the effect that volumetric feed flow rate has on separation efficiency for both bowl geometries. For the 65 x 400 mesh size fraction, the volumetric feed rate had little or no affect on separation efficiency for the short bowl. However, a 10% decrease in performance occurred with the long bowl when feed rate was reduced from 20 to 10 gpm. This is due to a longer retention time in the long bowl which allowed the coal particles the time to settle into the solids bed and report into the underflow. However, for the coarser +65 mesh size fraction, the retention supplied by the short bowl was sufficient enough to cause the coarse

![Graphs showing separation efficiency vs. volumetric feed flow rate](image)

**Figure 3.** Experimental results obtained from the Falcon Concentrator showing the effect of volumetric feed flow rate on separation efficiency for a) +65 mesh coal and b) 65 x 400 mesh coal and two different bowl geometries; feed solids = 16% by weight, g-force = 130.
coal particles to report to the underflow causing a decrease in recovery at low volumetric feed flow rates.

For volumetric flow rates greater than 20 gpm, separation efficiency slightly decreased from 50% to 45% at 40 gpm. An increase in volumetric flow rate may affect the separation performance for the following reasons: 1) reduction of the particle retention time, 2) increase in the chance of particle by-pass due to turbulence and 3) erosion of the solids bed causing beached gangue particles to report to the overflow. These effects would result in a increase in the product ash content which was observed for the results shown in Figure 3(a).

Test results showing the effect of centrifugal force on separation performance are shown in Figures 4(a) and (b) for the two bowl geometries. For the +65 mesh size fraction, separation efficiency decreased by nearly 10% for both bowl types when the applied g-force was increased from 70 to 200. This decline in separation efficiency is a result of a gradual decline in combustible recovery with little or no

![Graphs showing separation efficiency vs. centrifugal force](image)

**Figure 4.** Experimental results obtained from the Falcon Concentrator showing the effect of the applied g-force on separation efficiency for a) +65 mesh coal and b) 65 x 400 mesh coal and two different bowl geometries; feed solids = 16% by weight, volumetric feed flow rate = 20 gpm.
improvement in ash rejection. This trend results from the fact that the g-force required to allow the free gangue particles to report to the bowl wall has been surpassed and is sufficient to cause middling particles containing mostly coal to report to the inner layers of the beached solids near the bowl wall. The optimum g-force for this size fraction is about 50 according to predictions obtained by the empirical models.

On the other hand, the separation efficiency achieved by the long bowl remains virtually constant for the 65 x 400 mesh fraction up to a g-force of approximately 130. Beyond this value, separation efficiency declines by approximately 5%.

The shift in performance occurring at a g-force value of 130 agrees well with the optimum g-force of 120 predicted from an empirical expression for this size fraction. Figure 4(b) also shows that separation efficiency remains relatively unaffected over the entire range of g-force values studied. This may be explained by the inability of the coal particles to report to the inner portion of the beached solids due to the smaller retention time in the short bowl.

**Knelson Concentrator:** A test program based on a Box-Behnken design was also conducted on the Knelson Concentrator to optimize the operating parameter values. These tests were conducted and the data analyzed in the same manner as described previously for the Falcon Concentrator. The Knelson Concentrator has a set of pinch valves associated with each ring for discharging the heavy particles. The control system with the Knelson Concentrator allows one to control the pinch valves associated with the lower three rings independently of those with the upper three rings. Therefore, the opening and closing times of these valves are critical operating parameters along with volumetric feed rate. Initial tests defined an optimum fluidization water rate of 25 gpm. Since most of the heavies report in the lower rings, the opening time was held constant at a relatively low time of 0.4 seconds to prevent loss of combustible material. The bowl speed is fixed to provide a theoretical g-force of 60.

The parameter value ranges studied in the test program and their predicted optimum values are provided in Table 3. The optimum operating parameter values for the two size fraction were found to be basically the same. Maximum separation
Table 3. A list of the operating parameters of the Knelson Concentrator, the parameter value ranges studied in the Box-Behnken test program, and the optimum parameter values obtained for the treatment of an Illinois No. 5 coal slurry sample.

<table>
<thead>
<tr>
<th>Operating Parameter</th>
<th>Parameter Value Range</th>
<th>Optimum Parameter Value (+65 M)</th>
<th>Optimum Parameter Value (65 x 400 M)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feed Rate (gpm)</td>
<td>4 - 14</td>
<td>8.2</td>
<td>7.0</td>
</tr>
<tr>
<td>U.Closing Time (s)</td>
<td>5 - 30</td>
<td>14.8</td>
<td>16.0</td>
</tr>
<tr>
<td>L.Closing Time (s)</td>
<td>0.5 - 1.5</td>
<td>28.1</td>
<td>27.7</td>
</tr>
<tr>
<td>L.Opening Time (s)</td>
<td>5 - 30</td>
<td>1.0</td>
<td>0.87</td>
</tr>
</tbody>
</table>

Efficiency values of 48% and 55% were predicted from the empirical expressions for the +65 mesh and the 65 x 400 mesh size fractions, respectively.

Using the optimum parameter values, additional tests were conducted over a volumetric feed rate range of 4 to 14 gpm. As shown in Figure 5, separation efficiency gradually

![Graph showing separation efficiency vs. volumetric feed flow rate](image)

**Figure 5.** Experimental results obtained from the Knelson Concentrator showing the effect of volumetric feed flow rate on separation efficiency for the treatment of an Illinois No. 5 coal seam sample.
improved when increasing the volumetric flow rate up to 9 gpm. Further increasing the feed flow rate resulted in nearly a 20% drop in separation performance for both size fractions. This decrease in performance was due to the bypass of heavy mineral particles to the overflow, resulting in high product ash content values.

**Separation Performance**

The efficiency of a gravity-based process is typically measured by the partition curve which is generated from washability analysis data obtained from solid samples of the process streams. From the partition curve, the gravity cut-point \((D_{50})\) can be determined as well as the probable error \((E_p)\) value which is a measure of the process efficiency. The \(E_p\) value is determined by subtracting the density corresponding to a partition number of 75 \((D_{75})\) from the density value corresponding to the partition number of 25 \((D_{25})\) and dividing the number by a factor of 2. Highly efficient processes, such as dense-medium cyclones, generate \(E_p\) values of 0.05 and less efficient processes, such as spiral concentrators, produce \(E_p\) values between 0.12 and 0.20.

Figures 6(a) and 6(b) show the partition curves produced from the Falcon concentrator using the long and short bowl, respectively, under different centrifugal fields. For the long bowl, the \(D_{50}\) value decreased from 1.78 for a 72 g-field to 1.50 for a 199 g-field. This trend is due to an increase in the number of middling particles reporting to the underflow as the g-force is increased. The low \(D_{50}\) of 1.50 is a beneficial for the production of low ash content concentrates. As shown in Figure 6(b), the applied g-force in the short bowl had little affect on the \(D_{50}\) value which varied slightly between 1.55 and 1.60. This finding may be due to the larger vertical centrifugal force component in the short bowl which applies sufficient vertical force to move the heavies toward the underflow discharge port at a faster rate (i.e., lower particle retention time in the particle bed). Thus, middling particles do not have a chance to migrate through the bed of particles to the underflow ports. In the long bowl, a weak vertical force component exists which allows time for the horizontal component to drive the middling particles to the underflow port.
Figure 6. Partition curves produced from the treatment of the 65 x 400 mesh size fraction of an Illinois No. 5 fine coal seam sample using the Falcon Concentrator which utilized the (a) long bowl and (b) the short bowl.

From the partition curves in Figure 6(a), one can see that the separation efficiency as measured by the $E_p$ value
changed as a function of the centrifugal field for the log bowl. The best $E_p$ value of 0.10 was obtained for the 130 g-field at a feed rate of 20 gpm and a solids content of 16%. It is interesting to note that this is the same optimum conditions predicted from the empirical expressions described previously. Probable error values of 0.14 and 0.15 were achieved using g-forces of 199 and 72, respectively. For the short bowl, the $E_p$ value was found to be relatively constant at 0.10 with only a slight decrease in performance for the g-force of 72. This trend is consistent with that shown in Figure 4(b).

Partition curves were also generated for the +65 mesh size fraction. Generally, the $D_{50}$ value was found to vary between 1.7 to 2.0, which is higher than those obtained with the finer size fraction. The separation efficiency was also found to be substantially reduced. The $E_p$ value ranged from 0.25 to 0.40.

The test results shown in Table 4 summarize some of the better separation performances achieved to date. The results indicate that the Falcon concentrator has the ability to significantly reduce the ash content of the 28 x 100 and 100 x 325 mesh size fraction while achieving very high combustible recovery values of greater than 90%. These results were obtained at relatively high mass throughputs ranging from 0.4 to 1.0 tph/ft$^2$. The higher recovery values achieved by the 28 x 100 mesh size fraction indicates the ability of the Falcon unit to selectively withdraw through the underflow valves the inner portion of the solids bed

**Table 4.** Typical test results obtained on a size-by-size basis by the continuous Falcon Concentrator; volumetric feed rate = 20 gpm, feed solids content = 25% by weight, and bowl speed $\approx 1,100$ rpm.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Size (mesh)</th>
<th>Ash (%)</th>
<th>Ash Rej. (%)</th>
<th>Recovery (%)</th>
<th>Throughput (tons/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Feed</td>
<td>Product</td>
<td>Tailings</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Illinois No.5</td>
<td>+100</td>
<td>9.88</td>
<td>7.05</td>
<td>54.74</td>
<td>32.9</td>
</tr>
<tr>
<td></td>
<td>-100-325</td>
<td>17.63</td>
<td>8.30</td>
<td>79.29</td>
<td>59.1</td>
</tr>
<tr>
<td></td>
<td>-325</td>
<td>53.69</td>
<td>53.30</td>
<td>80.92</td>
<td>2.13</td>
</tr>
<tr>
<td>Illinois No.6</td>
<td>+100</td>
<td>4.47</td>
<td>3.66</td>
<td>11.50</td>
<td>26.6</td>
</tr>
<tr>
<td></td>
<td>-100-325</td>
<td>8.48</td>
<td>3.97</td>
<td>38.79</td>
<td>59.2</td>
</tr>
<tr>
<td></td>
<td>-325</td>
<td>62.37</td>
<td>61.29</td>
<td>88.96</td>
<td>5.59</td>
</tr>
<tr>
<td>Illinois No.5</td>
<td>+100</td>
<td>7.92</td>
<td>6.21</td>
<td>52.43</td>
<td>24.5</td>
</tr>
<tr>
<td></td>
<td>-100-325</td>
<td>12.80</td>
<td>7.33</td>
<td>66.29</td>
<td>48.1</td>
</tr>
<tr>
<td></td>
<td>-325</td>
<td>54.30</td>
<td>52.74</td>
<td>76.20</td>
<td>4.04</td>
</tr>
</tbody>
</table>
while allowing the outer portion containing the coarse coal particles to by-pass to the overflow.

The best separation performance was achieved on the 100 x 325 fraction which may be due to the relatively low ash content of the 28 x 100 mesh size fraction in the coal samples tested. The -325 mesh size fraction is not effectively de-ashed by the Falcon concentrator, however, previous tests have found that the -325 by approximately 10 μm fraction is significantly cleaned. This indicates that either a desliming device or a flotation column would be required to effectively reject submicron clay particles from the 28 x 0 size fraction.

The recovery-grade curve obtained by release analysis represents the best possible separation performance that can be achieved by a flotation process (Dell, 1964). Release analysis results obtained for the 28 x 100 mesh and 100 x 325 mesh size fractions of the Illinois No. 5 (2) coal sample are compared with the results obtained by the Falcon concentrator in Figures 7(a) and (b), respectively. In terms of ash rejection, the Falcon concentrator appears to provide a better or equal separation performance compared to

![Graphs](image)

**Figure 7.** A comparison between the separation performances achieved by release analysis and the Falcon concentrator in terms of ash rejection for the treatment of (a) 28 x 100 and (b) 100 x 325 mesh size fractions.
that expected from a froth flotation process for both size fractions.

The results presented in Table 4 were obtained from coal samples containing low-to-medium amounts of sulfur and ash-bearing material. Table 5 shows the results obtained from the treatment of the 65 x 400 mesh size fraction of an Illinois No. 5 coal sample containing 4.0% total sulfur, of which, 75% was pyritic sulfur. High rejections of pyritic sulfur were achieved while maintaining relatively high combustible recovery values. Ash contents were also substantially reduced to commercially acceptable levels.

**Table 5.** Results obtained from the treatment of a pyrite-rich 65 x 400 size fraction of an Illinois No. 5 coal sample using the Falcon Concentrator.

<table>
<thead>
<tr>
<th>Test Number</th>
<th>Ash (%)</th>
<th>Pyr. Sulfur (%)</th>
<th>Ash Rej. (%)</th>
<th>P. Sulfur Rej. (%)</th>
<th>Recovery (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feed</td>
<td>21.7</td>
<td>---</td>
<td>3.04</td>
<td>---</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>8.99</td>
<td>63.6</td>
<td>0.74</td>
<td>9.18</td>
<td>68.2</td>
</tr>
<tr>
<td>2</td>
<td>7.84</td>
<td>55.8</td>
<td>0.66</td>
<td>8.60</td>
<td>74.3</td>
</tr>
<tr>
<td>3</td>
<td>6.91</td>
<td>51.3</td>
<td>0.52</td>
<td>7.46</td>
<td>78.7</td>
</tr>
<tr>
<td>4</td>
<td>6.17</td>
<td>44.7</td>
<td>0.30</td>
<td>6.31</td>
<td>83.0</td>
</tr>
<tr>
<td>5</td>
<td>4.69</td>
<td>31.2</td>
<td>0.29</td>
<td>3.73</td>
<td>92.2</td>
</tr>
</tbody>
</table>

The pyritic sulfur rejection results in Table 5 are compared with those obtained from release analysis in Figure 8. As shown, the Falcon concentrator is superior in the rejection of coal pyrite as found in previous research on other enhanced gravity separators (Luttrell et al., 1993).

Figures 9(a) and (b) show a comparison between the results achieved by the Falcon and Knelson concentrators from the treatment of a 65 x 400 mesh size fraction of an Illinois No. 5 coal seam sample. The Falcon concentrator seemed to provide a slightly better separation performance. In terms of ash rejection, the Falcon consistently produced coal concentrates containing 5% to 10% ash from feed containing 21% while the Knelson unit generated products having ash contents between 9% and 13%. A similar comparison with the results obtained from the +65 mesh size fraction found that
Figure 8. A comparison between the pyritic sulfur rejection values achieved by release analyses and those obtained from the Falcon Concentrator for the treatment of a 65 x 400 mesh size fraction of an Illinois No. 5 coal sample.

Figure 9. A comparison of the separation performances achieved by the Falcon and Knelson Concentrators on the basis of (a) ash rejection and (b) total sulfur rejection for the 65 x 400 mesh size fraction.
the Knelson concentrator provided slightly better sulfur and ash rejections. The trend of providing slightly inferior results for the 65 x 400 mesh size fraction and superior results for the +65 mesh fraction may be a result of the lower g-force supplied by the Knelson concentrator as previously discussed. These results were obtained at mass flow rates of approximately 2 tph for the Falcon unit and flow rates less than 1 tph for the Knelson concentrator. Since Figure 5 indicates that increasing the flow to the Knelson negatively affects separation performance, the Falcon unit appears to have a throughput advantage.

Compliance Coal Production

Compliance coal has successfully, repeatedly, and consistently been produced from all coal feedstocks tested in this project. The following points help to underscore the magnitude and significance of these findings:

1. The production of these compliance coal products did not require any additional coal grinding. The feed streams tested on these units were bleed streams taken directly from the fine coal circuits on operating commercial coal preparation plants treating Illinois coals.

2. The units tested in this program were both full size commercial units. Units with bowl sizes up to 40 inches in diameter and rated to treat 50 to 150 tons of coal are for sale with no further scale-up or experimentation.

3. Compliance coal was produced from both mid-sulfur Illinois coal with over 50% organic sulfur and from high-sulfur Illinois coal containing a high pyrite content, and from both low and high ash coal feed stocks.

4. With an estimated operating cost of only $0.40/ton of coal treated, the enhanced gravity concentrators produce SO₂ emission reductions at costs lower than scrubbers, lower than SO₂ allowance purchases, and lower than competing fine coal cleaning technologies. In fact the reductions in SO₂ emissions were economical enough to produce salable emission allowances even in cases where the Illinois coal treated was already of compliance quality.
5. Both the Falcon and the Knelson Concentrators are capable of producing these compliance coal products, so the potential for competitive marketing of these enhanced gravity concentrators exists.

The data in Figure 10 were obtained from an untreated Illinois No. 5 fine coal circuit feed which was cleaned using the Falcon Concentrator. The results plotted represent the testing over a range of parameter values. A commercial operation will operate as close to the optimum grade-recovery curve indicated by the dotted and solid lines as economically and technically possible. Both the +65 and -65 mesh size fractions are brought into compliance with the 2.5 lb/million BTU limit from initial levels of over 7 lbs SO₂ per million BTU. For the +65 mesh size fraction, compliance is achieved with a combustible recovery of 87%, while the finer coal fraction achieves compliance with around 92% recovery. Size fractions down to 400 mesh were brought into compliance, indicating that essentially the entire fine coal feed stream could be processed to compliance through the Falcon unit with very little presizing or special feed preparation.

Figure 10. Results showing the production of compliance coal from a high-sulfur Illinois No. 5 coal sample using the Falcon Concentrator.
Figure 11 represents a similar plot for the Knelson Concentrator. Figure 11 clearly shows that the Knelson Concentrator achieves deep reductions in SO₂ emissions from over 7 lbs/MBTU down to about 1.9 lbs/MBTU. Combustible recovery for the +65 mesh fraction remains around 98% when compliance is reached. The sharpness of the separation achieved at +65 mesh suggests that the Knelson Concentrator makes a cleaner and more efficient separation than the Falcon unit in this size range. However, only one test achieved compliance on the -65 mesh size fraction, and that test resulted in only a 52% recovery of combustible material. This finding suggests that the Knelson Concentrator can only effectively be used to produce compliance coal from the coarser portion of the fine circuit feed. This would mean pre-sizing steps and a need for other coal processing units to be used on the -65 mesh size fractions at many preparation plants.

![Graph showing combustible recovery vs. product lbs SO₂/MBTU](image)

**Figure 11.** Results showing the production of compliance coal from a high-sulfur Illinois No. 5 coal sample using the Knelson Concentrator.

Enhanced gravity concentration is effective at producing compliance coal from mid-sulfur coal feedstocks even when most of the sulfur is organic, provided that it is pyritic sulfur that pushes the coal past the compliance limit. The effect is clearly shown for the 100 x 325 mesh fraction in
Table 6 where compliance is achieved with 99% combustible recovery and 1.9 lbs SO$_2$/MBTU is achieved with 90% recovery.

**Table 6.** Size-by-size sulfur reduction results achieved by the Falcon Concentrator from the treatment of the Illinois No. 5 (S2) coal sample; caloric values reported on an as-received basis.

<table>
<thead>
<tr>
<th>Test Number</th>
<th>Total Sulfur (%)</th>
<th>Product BTU/lb</th>
<th>Recovery (%)</th>
<th>Total Sulfur Rejection (%)</th>
<th>lb SO$_2$ per MBTU</th>
</tr>
</thead>
<tbody>
<tr>
<td>100 x 325</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>1.80</td>
<td>12,700</td>
<td>98.7</td>
<td>18.2</td>
<td>2.84</td>
</tr>
<tr>
<td>2</td>
<td>1.53</td>
<td>12,525</td>
<td>96.7</td>
<td>28.6</td>
<td>2.44</td>
</tr>
<tr>
<td>3</td>
<td>1.41</td>
<td>13,365</td>
<td>90.4</td>
<td>39.2</td>
<td>2.11</td>
</tr>
<tr>
<td>4</td>
<td>1.29</td>
<td>13,430</td>
<td>80.5</td>
<td>49.1</td>
<td>1.92</td>
</tr>
</tbody>
</table>

Another point realized by examination of Table 6 is that enhanced gravity concentration remains economically viable even when it is not used to produce compliance coal. It is noted that the 28 x 100 mesh fraction of this coal is already of compliance quality. The coal is cleaned from 2.14 lbs SO$_2$/MBTU to 1.8 lbs SO$_2$/MBTU with 95% recovery. With an estimated operating cost of $0.40/ton of coal treated, the reduction in SO$_2$ emissions costs for the Falcon Concentrator is $118/ton of SO$_2$. The ultra compliance reductions achieved produce salable SO$_2$ credits that currently trade for around $180/ton, and if based entirely on reductions achieved by scrubbing would probably trade for $300/ton. Although, in this project, every feedstock tested was cleaned to compliance levels, it is realized that there are Illinois Basin coals for which the organic sulfur level exceeds compliance. The magnitude of success demonstrated by this project will be understated if it is not realized that enhanced gravity concentration remains the lowest cost sulfur reducing technology and is an economically viable way to enhance the competitive position of these coal feedstocks as well.
Toxic Trace Compliance

This project made a preliminary examination of the elimination of toxic trace elements by enhanced gravity concentration. Several points should be understood in examining the impact physical cleaning has on toxic trace elimination.

1. The regulations on toxic emissions have not been set yet. Further, the fate and distribution of toxic trace elements between fly ash, bottom ash, and airborne emission remains a function of the carrier phase in the fuel and the operating conditions at the power plant. Thus, there is no compliance level concentration for trace elements in fuel.

2. Because many traces are equally distributed in the organic and inorganic phases, there may be no single target mineral to eliminate, such as pyrite is the target for sulfur elimination.

3. Trace element quantification is not equal in precision to the quantification of sulfur content. In this study, the product and tailing samples were acid digested by the method of Nadkarni (1984). The digestion utilized aqua regia and hydrofluoric acid under vacuum in a microwave. The solubilized sample was then analyzed by ICP and AA. Results of 4 pairs of product and tails from operating conditions optimized for sulfur rejection were averaged to produce the final data.

Those elements that appear to move with the pyrite are shown in Figure 12, and show deep reductions in concentration relative to the untreated feed. From a toxic trace standpoint, the reductions in cadmium and lead are the most significant. Cleaning results for these elements exceed what could be hoped for in most coal desulfurization processes.

Those elements that appear to move with the ash and organic phases are shown in Figure 13. Results for these elements are roughly what would be expected for coal desulfurization if the non-organic sulfur was carried by the ash phase rather than pyrite. The most significant elements in this group are arsenic and vanadium.
Figure 12.  Trace element reductions associated with coal pyrite achieved by the Falcon Concentrator.

Figure 13.  Trace element reductions achieved by the Falcon Concentrator which are associated with the ash-bearing components/organic phase.
The last group of elements shown in Figure 14 have high organic associations. Clearly, even with these elements, there is an ash component because the tailing concentration exceeds the feed concentration, but the product material shows only token reductions in trace levels. The most problematic element in this group is chromium.

![Graph showing concentration relative to feed for Mo, Cr, Co, and Ni]

**Figure 14.** Trace element reductions achieved by the Falcon Concentrator which have a high affinity for the organic phase.

Several other trace elements were studied but measured levels and detections were low enough that quantitative results should be studied further. A project looking directly at trace element distributions next year will use special analytical techniques (graphite furnace and hydride formation) for those key elements for which concentrations are extremely low. Low levels of beryllium were detected in both the concentrates and tails, but no preferential distribution to either phase was observed. Selenium was detected in half of the tailing samples and none of the concentrates. Mass balances indicate a feed content of 3.5 parts per million in the solid phases. All of the selenium appears to have gone to the tails with a concentration of 15.3 ppm. It should be noted that concentrations in solution are above the detection limit for the tails
concentration, but within the background equivalent concentration. Failure to detect selenium in the concentrates could indicate a concentration below detection limits or within the background noise levels for the instrument, rather than an absence of selenium in the concentrates. If selenium is still present in the concentrates, it is almost certainly at lower concentration than in the tailings, but a conclusion that all selenium is removed by centrifugal washing is questionable without the additional work in next years project. Mercury was also studied by cold vapor AA with low ppm detections in the digestion products. The feed concentration arrived at by mass balance was 10.7 ppm, with 11.25 ppm in the tails and 10.5 ppm in the concentrates. These figures would make the partitioning of mercury almost identical to that of chromium. Completeness of the mercury recovery in the Nadkarni process is to be tested further in next years project.

CONCLUSIONS

1. Enhanced gravity concentration was successful at producing Phase I compliance coal from all feed streams tested. Success was achieved on coals with varying degrees of prior processing, ranging from untreated fines circuit feed to flotation circuit feed. Compliance coal was produced from low-to-high ash content coals. The sulfur contents ranged from 1.3% to 4.0% with the organic sulfur content being approximately 1% for all the coal samples tested. For the high sulfur content coal sample, the total sulfur content was reduced to 1.4% which was a result of high pyritic sulfur rejections ranging from 80% - 98%. An 85% rejection of pyritic sulfur at a combustible recovery of 85% was found to be achievable for both the Falcon and Knelson concentrators.

2. Ash-forming material was found to be substantially rejected in the 28 x 400 mesh size fraction by both concentrators. At 2.1 tph, the ash content of the 100 x 325 fraction in an Illinois No. 5 coal sample was reduced from 18% to 8% using the Falcon Concentrator with a high combustible recovery of 97%. Both concentrators, however, were found to be ineffective at
treating the -400 mesh size fraction or, more specifically, the slime material.

3. The performance of enhanced gravity concentration in trace element reduction depends on the association of the trace element. Toxics, such as cadmium and lead which have an affinity for pyrite in the samples tested, were almost totally eliminated. Other toxic elements, such as arsenic that appear to have an organic and ash affinity, were removed only to the extent that the coal was de-ashed. Toxics, such as chromium, that appear to be highly organically linked, were not rejected by the gravity concentrators.

4. The Falcon Concentrator was found to be more efficient at treating the 65 x 400 mesh size fraction while the Knelson Concentrator was more effective in cleaning the +65 mesh size fraction.

5. The Falcon Concentrator was found to be effective at treating a large range of volumetric flow rates between 10 and 40 gpm at a solids content of 16% by weight. The corresponding mass flow rate for a 40 gpm flow rate is about 2 tph. The Knelson concentrator was found to be limited to approximately 10 gpm which corresponds to a mass flow rate of nearly 1 tph.

6. Partition curves revealed that the Falcon concentrator has the ability to achieve relatively low gravity cuts ($D_{50}$) ranging from 1.5 to 1.7 for the 65 x 400 size fraction. The $D_{50}$ values obtained for the coarser +65 mesh size fraction ranged from 1.7 to 2.0.

7. The separation efficiency achieved by the Falcon Concentrator for the treatment of the 65 x 400 mesh size fraction was excellent. The $E_p$ values achieved for this fraction ranged from 0.10 to 0.15. However, treatment of the +65 mesh size fraction was less efficient as indicated by $E_p$ values ranging from 0.25 to 0.40.

8. Bowl geometry was found to be critical for determining the separation performance of the Falcon Concentrator. The magnitude of the applied centrifugal force was found to effect the $D_{50}$ value achieved by the use of a
long bowl. A low gravity cut point of 1.5 could be achieved by increasing the g-force to 200g. However, this effect was not realized for the short bowl. The D50 value and the Ep value remained unchanged over a g-force range of 70g to 200g.

REFERENCES


