The main objective of the project was to develop a highly efficient enhanced gravity separation (EGS) process for cleaning fine coal (16 x 325 mesh) using dense medium. Extensive test work was conducted on both dense medium (D.M.) and water-only EGS processes using the Falcon Concentrator as the EGS unit, two easy-to-clean coal samples and two difficult-to-clean middling samples as feed. Statistically designed experiments were conducted to optimize the performance of the dense medium and water-only Falcon processes. Under optimum conditions, the D.M. Falcon process provided a clean coal yield of 78.8% with 5.7% ash and 2.9% total sulfur for an Illinois No. 6 seam coal containing 15.5% ash and 3.8% total sulfur. The pyritic sulfur content was reduced from 1.2% to 0.6%. For another easy-to-clean Illinois No. 6 seam coal with 17.5% ash and 1.5% total sulfur, the D.M. Falcon process achieved a clean coal yield of 78.9% with product ash and total sulfur contents of 5.7% and 1.0%, respectively. According to feed washability analysis data for both coals, these separation performances equate to an organic efficiency of nearly 99% and a 7% weight unit improvement in clean coal yield compared to the optimized water-only Falcon process results. Treatment of an Illinois No. 5 middling sample by the D.M. Falcon process reduced the feed ash and total sulfur contents from 22.3% and 2.5% to 7.5% and 1.6%, respectively, while recovering 62.2% of the feed mass to the product. Another Illinois No. 5 middling sample having 29% feed ash was cleaned to 6.9% ash with 51.6% yield in the D.M. Falcon. The feed total and pyritic sulfur contents were reduced to 1.5% and 0.8% from a feed of 2.8% and 1.7%, respectively. For the difficult-to-wash middling samples, the D.M. Falcon provided a 16% weight unit improvement in clean coal yield over the water-only process and achieved an organic efficiency greater than 90%. The water-only and D.M Falcon processes were also able to produce Phase I compliance coal from the middlings samples, which had an estimated SO₂ emission greater than 4.5 lbs/MBTU in the feed. Performance simulations conducted for the Illinois No. 5 plant indicate a 4.1% increase in clean coal yield at current target product quality levels by replacing the existing spiral circuit with D.M. Falcon. Preliminary economic analysis revealed that the clean coal yield improvement translates to a $4.2 million increase in annual income after discounting the capital cost invested at a rate of 12% per annum. The combination of a high “g” force and dense medium seems to provide excellent separation efficiency for cleaning the 16 x 325 mesh particle size coal.
EXECUTIVE SUMMARY

The major goal of this project was to develop a highly efficient, high capacity enhanced gravity concentration process using dense medium for treating the –28 mesh particle size fraction in coal preparation plants. The test program evaluated a novel application of magnetite-based heavy media in a continuous enhanced gravity separator (EGS) commercially known as the Falcon Concentrator.

Funding provided by the ICCI and Illinois coal companies has facilitated test programs to be conducted by the principal investigator which have revealed that relatively low $D_{50}$ values of about 1.6 can be achieved on the 28 x 325 mesh particle size fraction using water-only enhanced gravity separation technologies. This separation was achieved in a full-scale Falcon Concentrator treating 75 tons/hr of feed at a volumetric feed rate of 1800 gallons/minute. However, the corresponding $E_p$ values are between 0.12 and 0.18, which are comparable to those associated with spiral concentrators. Though these $E_p$ values may represent an acceptable efficiency at the high gravity cut-points, gravity cut-points lower than 1.6 typically results in significant loss in mass yield due to the increase in the amount of near-gravity material and the relative process inefficiencies. Thus, a unit operation providing an even lower $D_{50}$ value than the 1.60 value and a higher separation efficiency is needed to realize the yield optimization goal of the proposed project.

Previous studies conducted on the Falcon Concentrator have found that a significant amount of coal in the 28 x 100 mesh particle size fraction is lost to the tailings. Though the high $g$-force provided by the Falcon concentrator enhances the separation efficient of the finer particle size fractions (100 x 325 mesh), it also leads to faster settling of the coarse coal into the particle bed, which reports to the tailings process stream. It is believed that, by using a dense medium in the Falcon Concentrator, the stratification of the particle bed is more controlled and the effect of particle size during the separation process is greatly reduced. Preliminary feasibility test results validated this hypothesis.

The proposed project objective was only to test 28 x 325 mesh particle size coal. However, installation of new underflow nozzles in the C10 Falcon Concentrator, which eliminated the plugging problem realized during a previous investigation, allowed successful testing of a wider particle size range, i.e., 16 x 325 mesh. The new nozzles provide a variable diameter, for which, the size is controlled by compressed air.

Four different coal samples were treated in both dense medium and water-only Falcon processes. Coals No. 1 and 2 were collected from operating coal preparation plants treating coal from the Illinois No. 6 seam. Based on washability analysis data, both coals were characterized as easy-to-clean with Coal No. 1 being a high sulfur coal. Coals No. 3 and 4 were collected from the middling stream of spiral concentrators installed at a preparation plant treating Illinois No. 5 seam coal. Both middling sample sources are currently waste streams. Coals No. 3 and 4 contained a significant amount of near gravity material and, thus, were characterized as difficult-to-clean. Therefore, effective
treatment of the two middling coals would indicate a high level of efficiency for any gravity-based process.

Experiments based on a Plackett-Burman design were conducted on the dense medium Falcon operation to identify the most significant process variables. Based on these results, four important process variables were identified for a more detailed test program conducted according to a Box-Behnken design. Separation performance results were used to evaluate the effect of the process variables and optimize the performance of the dense medium enhanced gravity separation. Statistically designed experiments were also conducted to optimize the performance water-only Falcon process.

Table 1 shows the optimum performances achieved for the two easy-to-clean coals for the dense medium (D.M.) and water-only (W.O.) Falcon processes. The results indicate that the dense medium process provides a superior separation performance resulting in a 7.8% weight unit increase in clean coal yield over the water-only results at the given product quality level. Optimization validation experiments confirmed the reproducibility and the performance of the dense medium operation. A comparison with feed washability data indicated that the dense medium process provided an organic efficiency nearly 99%. The partition curves obtained for the dense medium Falcon process indicated that a density cut point of 1.41 was achieved with a low probable error \( E_p \) value of 0.038 compared to that of 0.075 normally achieved in conventional fine coal cleaning using dense medium cyclones.

Table 1. Optimum separation performance achieved in dense medium and water-only Falcon processes for treating Coals No. 1 and 2.

<table>
<thead>
<tr>
<th>Coal No. 1</th>
<th>Coal No. 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feed</td>
<td></td>
</tr>
<tr>
<td>Ash (%)</td>
<td>D.M.</td>
</tr>
<tr>
<td>Total sulfur (%)</td>
<td>15.5</td>
</tr>
<tr>
<td>Pyritic sulfur (%)</td>
<td>3.8</td>
</tr>
<tr>
<td>BTU/lb</td>
<td>11386</td>
</tr>
<tr>
<td>lbs SO2/ MBTU</td>
<td>6.67</td>
</tr>
<tr>
<td>Product</td>
<td></td>
</tr>
<tr>
<td>Ash (%)</td>
<td>6.2</td>
</tr>
<tr>
<td>Total sulfur (%)</td>
<td>2.9</td>
</tr>
<tr>
<td>Pyritic sulfur (%)</td>
<td>0.6</td>
</tr>
<tr>
<td>BTU/lb</td>
<td>13586</td>
</tr>
<tr>
<td>lbs SO2/ MBTU</td>
<td>4.22</td>
</tr>
<tr>
<td>Clean coal yield (%)</td>
<td>78.8</td>
</tr>
<tr>
<td>Organic efficiency (%)</td>
<td>99.2</td>
</tr>
<tr>
<td>Density cut-point, ( d_{50} )</td>
<td>1.41</td>
</tr>
<tr>
<td>Probable error, ( E_p )</td>
<td>0.038</td>
</tr>
</tbody>
</table>
The dense medium process was also able to achieve high quality products, i.e., low ash content, with reasonable clean coal yield values. For example, a product containing 3.9% ash was achieved while recovering 62.7% of the feed material to the product. In comparison, the ultimate froth flotation performance as predicted by the Advanced Flotation Washability (A.F.W.) indicates only a 36.7% yield to the product at the same product grade.

The optimum performances of the dense medium and water-only Falcon processes treating the more difficult-to-clean Coals No. 3 and 4 are summarized in Table 2. The dense medium process performed well with an organic efficiency above 90%. Reflective of the high efficiency of the D.M. process and the difficult-to-clean characteristics, the improvement in clean coal yield of 17% weight units was significantly higher than the differential obtained for Coals No. 1 and 2. The dense medium process provides a more effective stratification of the near gravity material and reduces misplacement, which results in higher clean coal yield values at the same product quality levels.

Table 2. Optimum separation performance achieved in dense medium and water-only Falcon processes for treating Coals No. 3 and 4.

<table>
<thead>
<tr>
<th></th>
<th>Coal No. 3 D.M.</th>
<th>Coal No. 3 W.O.</th>
<th>Coal No. 4 D.M.</th>
<th>Coal No. 4 W.O.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Feed</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ash (%)</td>
<td>22.3</td>
<td>22.3</td>
<td>29.0</td>
<td>29.0</td>
</tr>
<tr>
<td>Total sulfur (%)</td>
<td>2.5</td>
<td>2.5</td>
<td>2.8</td>
<td>2.8</td>
</tr>
<tr>
<td>Pyritic sulfur (%)</td>
<td>1.7</td>
<td>1.7</td>
<td>1.7</td>
<td>1.7</td>
</tr>
<tr>
<td>BTU/lb</td>
<td>10691</td>
<td>10691</td>
<td>9593</td>
<td>9593</td>
</tr>
<tr>
<td>lbs SO₂/ MBTU</td>
<td>4.68</td>
<td>4.68</td>
<td>5.38</td>
<td>5.38</td>
</tr>
<tr>
<td><strong>Product</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ash (%)</td>
<td>7.5</td>
<td>7.8</td>
<td>6.9</td>
<td>8.1</td>
</tr>
<tr>
<td>Total sulfur (%)</td>
<td>1.6</td>
<td>1.9</td>
<td>1.5</td>
<td>1.5</td>
</tr>
<tr>
<td>Pyritic sulfur (%)</td>
<td>0.4</td>
<td>0.6</td>
<td>0.8</td>
<td>0.8</td>
</tr>
<tr>
<td>BTU/lb</td>
<td>13190</td>
<td>12696</td>
<td>13394</td>
<td>13033</td>
</tr>
<tr>
<td>lbs SO₂/ MBTU</td>
<td>2.18</td>
<td>2.5</td>
<td>2.32</td>
<td>2.22</td>
</tr>
<tr>
<td>Clean coal yield (%)</td>
<td>62.2</td>
<td>45.3</td>
<td>51.6</td>
<td>32.8</td>
</tr>
<tr>
<td>Organic efficiency (%)</td>
<td>91.3</td>
<td>66.6</td>
<td>93.8</td>
<td>60.6</td>
</tr>
<tr>
<td>Density cut-point, (d_{50})</td>
<td>1.43</td>
<td>1.55</td>
<td>1.49</td>
<td>1.55</td>
</tr>
<tr>
<td>Probable error, (E_p)</td>
<td>0.048</td>
<td>0.128</td>
<td>0.055</td>
<td>0.178</td>
</tr>
</tbody>
</table>

Additional experiments were conducted on a Humphrey spiral concentrator using Coal No. 4 as feed to compare the performances of dense medium and water-only enhanced gravity separation processes with the conventional fine coal cleaning operation. Due to inherent inefficiencies involved in the spiral process, the product ash content could not be reduced below 18.9%, which was achieved while yielding 61.9% of the feed mass to the product. The total and pyritic sulfur contents were reduced only to 2.3% and 1.3%, respectively.
respectively. The inability of the spiral process to achieve density cut points below 1.8 is the main reason for the poor performance. At a comparable product ash level (18.9%), the clean coal yields obtained from the dense medium and water-only Falcon processes were 74% and 65%, respectively. It may also be noted from Table 2 that both dense medium and water-only processes were able to produce Phase I compliance coal from the middling samples.

A preliminary study evaluating the effect of magnetite particle size distribution on the performance and expected loss of medium from the dense medium Falcon process was conducted. Experiments conducted using fine (d_{80} = 17 microns) and coarse (d_{80} = 31 microns) magnetite for treating Coal 4 showed that process efficiency is not affected by the use of coarse magnetite. The dense medium recovery studies were conducted using a wet drum magnetic separator arranged in rougher-cleaner-scavenger circuit. The coal slurry with the fine magnetite as dense medium was used in the media recovery studies to provide the worst case scenario. The media loss was found to be about 3 kgs/ton of raw coal treated. The use of the coarse magnetite will reduce the loss without significantly affecting the dense medium Falcon process efficiency.

Using the performance data obtained from the dense medium Falcon process, computer simulations were conducted to evaluate the benefits expected for the overall coal preparation plant operation. Computer programs and data generated during a previous ICCI project investigation were used to optimize the existing plant operation and evaluate the improvement achieved by replacing the conventional fine coal cleaning devices with the dense medium Falcon process. The processing plant evaluated in this study treats Illinois No. 5 seam coal in four circuits consisting of a dense medium bath, cyclones, spirals and conventional froth flotation. At the current product quality levels of 8% ash and 1.1% total sulfur, replacing spirals by the dense medium Falcon provided a 4.1% weight unit improvement in overall plant clean coal yield. A preliminary economic analysis was also conducted to evaluate the monetary benefits of using the dense medium Falcon operation. The requirements for additional capital cost and recurring costs such as dense medium loss were taken into consideration. The economic analysis predicted a $4.2 million increase in annual income due to the dense medium enhanced gravity separation after discounting the capital cost invested at a rate 12%.

The extensive evaluation conducted in this investigation indicates that the dense medium Falcon operation is a unique high efficiency and high capacity process for treating coal over a wide particle size range, i.e., 16 x 325 mesh. Apart from the techno-economic benefits, the dense medium Falcon may also provide operational flexibility such as the ability to achieve a wide variation in separation density cut points (d_{50}) without changing the feed medium density. For example, a range of density cut points from 1.4 to 1.6 was achieved by manipulating bowl speed and underflow valve air pressure while maintaining the feed medium density at 1.5. The dense medium Falcon process is also amenable to on-line process control to achieve optimum process and plant efficiency while producing target product qualities.
OBJECTIVES

The overall goal of the proposed project was to develop an advanced fine coal cleaning technology that provides a significant improvement in the separation efficiency currently achieved from the treatment of fine coal. In addition, the process was to show the ability to achieve efficient separations at relatively high mass throughput capacity values while also being amenable to on-line control for plant optimization purposes. The specific project objectives were to:

- Evaluate and optimize the performance of the dense medium Falcon operation for coals of different characteristics;
- Compare the dense medium and water-only Falcon performances with special reference to feed coal characteristics;
- 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.

As shown in previous studies, enhanced gravity concentrators have limited ability to treat the -325 particle size fraction. Furthermore, the presence of substantial amounts of -325 material in a dense medium separation is detrimental to the separation performance due to an increase in slurry viscosity. Thus, an objective of this investigation was also to evaluate systems for the potential of achieving an effective 325 mesh particle size separation using available technologies and selecting the appropriate de-sliming method for the dense medium Falcon operation. A schematic flowchart envisaged for the dense medium Falcon operation is given in Figure 1.

INTRODUCTION AND BACKGROUND

About 20% of the total run-of-mine coal is treated in the fine coal (-28 mesh) cleaning circuit. Despite the fact that the coal in this range is more liberated than the coarser particle size fractions, achieving efficient separation has always been a problem in operating coal preparation plants. In fact, these problems have led to decisions by a number of coal companies to dispose of the entire fine coal fraction rather than to recover the well-liberated fine coal. Thus, substantial losses in potential revenue are commonly incurred. Conventional gravity and flotation techniques fail to treat the fine coal efficiently due to:

- lack of gravity/centrifugal acceleration to enhance the differential settling of fine coal and ash-forming material, which results in poor separation efficiencies and low throughput capacities per process per unit cross-sectional area;
• entrainment of sub-micron ash forming material in the process water reporting to the fine clean coal concentrates of gravity-based and froth flotation processes, which is detrimental to product grade;
• non-desirable hydrodynamic environment for bubble-particle attachment in froth flotation which results in a lower recovery of coal particles;
• flotation of coal pyrite which increases the sulfur content of the fine coal concentrate.

In the past two decades, most of the research in the coal preparation area has been directed to find solutions for the above mentioned problems. These efforts have resulted in more efficient fine coal cleaning technologies, such as column flotation and enhanced gravity separation.

A focus of several recent investigations is the use of enhanced gravity separators (EGS) for achieving high capacity, highly efficient fine coal cleaning. In a research project funded by ICCI, CONSOL, and the manufacturer, the principal investigator found that a full-scale Falcon C10 unit has the ability to efficiently clean –16 mesh coal at throughput capacities greater than 100 tons/hr. In fact, the effective specific gravity cut point \( D_{50} \) between 1.6 and 1.7 and a probable error \( E_p \) value of 0.12 obtained from the full-scale Falcon unit represent a significant improvement in the separation performance currently achievable by conventional technologies for the treatment of fine coal. However, recent coal preparation optimization studies have revealed that substantial increases in the overall plant yield and, thus mine profitability can be realized if lower \( D_{50} \) values could be achieved from the treatment of the fine coal while maintaining a high separation efficiency (e.g., \( E_p \) value approaching zero). As a result, the principal investigators initiated research to develop a novel fine coal cleaning process which will provide the desired separation performance described above at a relatively high capacity. This effort led to the dense medium Falcon system described in this report.

The use of heavy media in the Falcon Concentrator was initially applied to assist in the recovery of coarse coal particles that were lost to the tailings stream in the water-only experiments. This coal loss was a result of the particle size dependency of water-based separation. The heavy media de-emphasizes the particle size effect by having a pulp density that is greater than that of solid coal and, thus prevents the coarse coal from reporting to the tailings stream.

**EXPERIMENTAL PROCEDURE**

**Test Samples**

The dense medium and water-only Falcon tests were conducted on four different coal samples collected from operating Illinois coal preparation plants. The feed characteristics of the coal samples tested are given in Table 3. In addition, experiments were also conducted on a Humphrey’s spiral concentrator using Coal No. 4 as feed for comparing the performance of dense medium Falcon with conventional fine coal cleaning unit. Each of the samples were 100% minus 16 mesh.
Figure 1. Schematic diagram of the flowchart envisaged for the dense medium Falcon operation.
Table 3. Feed characteristics of the coal samples treated by the various processes in this investigation. Washability descriptions were defined by ASTM washability analysis results.

<table>
<thead>
<tr>
<th>Coal</th>
<th>Source</th>
<th>Washability Description</th>
<th>Feed grade</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. 1</td>
<td>Illinois No 6 seam</td>
<td>Easy-to-clean High total sulfur</td>
<td>Ash = 16.5% T. Sulfur = 3.8% Pyritic Sulfur = 1.2%</td>
</tr>
<tr>
<td>No. 2</td>
<td>Illinois No 6 seam</td>
<td>Easy-to-clean</td>
<td>Ash = 15.5% T. Sulfur = 1.5% Pyritic Sulfur = 0.6%</td>
</tr>
<tr>
<td>No. 3</td>
<td>Illinois No 5 seam</td>
<td>Difficult-to-clean</td>
<td>Ash = 22.5% T. Sulfur = 2.5% Pyritic Sulfur = 1.6%</td>
</tr>
<tr>
<td>No. 4</td>
<td>Illinois No 5 seam</td>
<td>Difficult-to-clean</td>
<td>Ash = 29.0% T. Sulfur = 2.8% Pyritic Sulfur = 1.7%</td>
</tr>
</tbody>
</table>

Two different magnetite samples, i.e., fine and coarse, were used as dense medium. The particle size distributions of the magnetite samples are presented in Figure 2.

![Figure 2](image_url)
Dense Medium Falcon Experiments

The dense medium Falcon experiments were conducted using continuous C10 concentrator. A schematic diagram of the experimental setup is provided in Figure 3. Prior to each test, the feed sump was filled with a measured quantity of water and the coal sample was added to obtain the required feed solids content. The coal sample was prescreened using a 16 mesh screen to remove the oversize material. A pre-calculated amount of magnetite was then added to the feed sump to obtain the required medium density. The slurry in the feed sump was kept in suspension using two stirrers and recirculation circuit. During the experiments, the feed sump was frequently checked to avoid settling of particles. After verifying the feed density, the desired feed flow rate was set by adjusting the by-pass valve. The required operating levels of the Falcon concentrator, such as the bowl speed and air pressure, were set. The feed, concentrate and tailing samples were collected after allowing sufficient time for attaining steady-state conditions. The samples collected were screened over a 325-mesh screen to separate the coal and magnetite.

Figure 3. Schematic diagram of the experimental setup used for the dense medium Falcon tests.
RESULTS AND DISCUSSIONS

Since the application of dense medium in enhanced gravity separation was a novel concept, a test program based on a Plackett-Burman was performed to identify the important process variables for further detailed studies. Four important process variables were realized and include feed medium density, bowl speed, underflow valve air pressure and feed volumetric flow rate. The effect of major operating variables on the performance of the dense medium Falcon process is discussed in the following.

Effect of Feed Medium Density

In conventional dense medium processes (dense medium cyclones and baths), an increase in medium density increases the clean coal yield and product ash content. The experimental results of the dense medium Falcon process treating Coal No. 1 (Illinois No. 6 seam coal) showed a similar trend, i.e., increase in feed medium density increased the clean coal yield and product ash. In these experiments, the medium density was varied between 1.3 and 1.45. However, the dense medium Falcon results obtained from treating Coal No. 4 (Illinois No. 5 seam middling sample) showed a different effect of feed medium density on the clean coal yield. Figure 4 shows the relationship between clean coal yield and feed medium density for Coal No. 4 at different air pressure levels. The negative effect of medium density in the dense medium Falcon may be attributed to the separation mechanism in the process.

Figure 4. Effect of feed medium density on the clean coal yield of the dense medium Falcon process treating Coal No. 4 (Illinois No. 5 middling sample) at different air pressure levels (bowl speed = 40 Hz).
At a higher medium density, the feed slurry contains a high amount of magnetite (>40% by weight), which might be quickly settling to the wall under high centrifugal acceleration provided in the enhanced gravity separation thus resulting in a low effective medium density slurry. It is also possible that the major movement of magnetite medium towards the wall at high medium densities traps light coal particles near wall resulting in decrease of yield. Irrespective of the reason, the results indicate there is strong interactional effect between process variables and feed coal characteristics and these findings need further investigation.

One of the major advantages found in the dense medium Falcon process is its ability to achieve lower density cut points than that of the medium density, which is not possible in other dense medium processes. For example, a density cut point of 1.43 was achieved while maintaining the feed medium density at 1.5. The density cut point in the dense medium Falcon can be varied over a wide range by adjusting the underflow valve air pressure.

Effect of Feed Flow Rate

The results indicate that the volumetric feed flow rate has minimal effect on the performance. Increase in feed flow rate increases the clean coal yield but reduces the overall separation efficiency. An appropriate selection of feed flow rate should be made based on the feed coal characteristics. Higher flow rates can be used for an easy-to-clean coal while lower feed flow rates will be suitable for a difficult-to-wash coal sample. Figure 5 illustrates the variation of clean coal yield and separation efficiency with feed flow rate.

![Figure 5. Effect of feed medium density on the clean coal yield and separation efficiency of the dense medium Falcon process.](image-url)
Effect of Bowl Speed

Bowl speed and underflow valve air pressure have the greatest interactional effect on the performance of the dense medium Falcon process. The results obtained from a Box-Behnken design of experiments was used to study the effect of bowl speed on important performance factors such as combustible recovery, ash rejection and total sulfur rejection. Using a commercially available statistical package, the effect of bowl speed was simulated over the range of experimental studies keeping other variables constant as shown in Figure 6. The simulation results were based on a well-fitted quadratic model to the experimental results.

The simulation results indicate that an increase in bowl speed decreases the combustible recovery while increasing the ash and total sulfur rejection values. An increase in bowl speed provides a higher applied “g” force in the enhanced gravity separator, thereby allowing faster settling of particles to the wall which eventually pass through the underflow nozzles.

Figure 6. Effect of bowl speed on the separation performance of the dense medium Falcon process as predicted from empirical models developed from the experimental data.
Effect of Air Pressure

During this project investigation, newly developed advanced nozzles were fitted to the C10 Falcon Concentrator underflow port. These nozzles provide precise control of the underflow rate with a variable nozzle diameter to achieve better metallurgical performance. In the earlier system, the underflow rate was controlled by adjusting the opening and closing time of the fixed diameter nozzles. The new underflow nozzle diameter is controlled by compressed air and the nozzle diameter is varied by adjusting the air pressure. The new nozzles may be purged to remove oversize material without shutting down the operation. Earlier studies have shown that underflow nozzle plugging as an operational difficulty for the Falcon Concentrator. The design of the new nozzle system eliminates the plugging problem since the underflow opening size could be varied automatically during the operation.

The effect of air pressure on the performance was evaluated similar to that of bowl speed and these results are presented in Figure 7. An increase in air pressure restricts the underflow nozzle diameter resulting in higher combustible recovery and lower ash and total sulfur rejections. However, the effect and range of the dense medium Falcon process variables seem to be dependent on the feed coal characteristics.

![Figure 7. Effect of air pressure on the separation performance of the dense medium Falcon process as predicted from empirical models developed from the experimental data.](image-url)
Coal No. 1 – Illinois No. 6 Seam Coal

This coal is classified as easy-to-clean, but contained a large amount of sulfur. The feed ash, total and pyritic sulfur contents were 15.5%, 3.8% and 1.2%, respectively. A Box-Behnken design of experiments was conducted on the dense medium Falcon Concentrator to evaluate the interactional effect of the process variables and optimize the process. Variables chosen for this study and their ranges were

- Feed medium density (gm/cc): 1.3 – 1.45
- Feed flow rate (gpm): 13 – 30
- Bowl speed (Hz): 20 – 40
- Air pressure (psi): 85 – 95

Experiments were also conducted on the water-only Falcon Concentrator to compare the performances. Process variables and their ranges were obtained from the results of earlier ICCI projects. Using the results obtained from the statistically designed experiments, both the dense medium and water-only Falcon process were optimized. Validation experiments were conducted at the optimum levels of the operating variables. Experimental results have indicated that a clean coal product containing 6.2% ash with 90% combustible recovery was achieved from the dense medium Falcon process treating the Illinois No. 6 coal sample having a feed ash content of 15.5%. The total sulfur content was reduced to 2.9% from 3.8% while the pyritic sulfur content was reduced to 0.6% from 1.2%. The performance comparison of water-only and dense medium Falcon processes in terms of the clean coal yield with corresponding product ash and total sulfur contents are shown Figures 8(a) and (b), respectively, along with feed washability and Advanced Flotation Washability (A.F.W) results. From these results, the following important observations were made:

- The performance of the dense medium Falcon process is very close to the washability curve, which represents the ideal separation possible by the physical separation. The organic efficiency of the dense medium Falcon process was found to be nearly 99%.
- Improvement in clean coal yield due to the application of dense medium was found to be about 7% weight units at the product ash content of 6.2%. The improvement in clean coal yield is much higher at lower clean coal ash contents.
- Many performance points of the dense medium Falcon process are above the A.F.W. curve, which is the best separation performance possible by any flotation technology.
- The validation experiments conducted at optimum process variable levels confirm the excellent separation performance achieved in the dense medium Falcon process.

The pyritic sulfur contents of the selected products of dense medium and water-only Falcon experiments were analyzed and these results were compared with washability and A.F.W results in Figure 9. As expected, the pyritic sulfur rejection performances of both the dense medium and water-only Falcon process were superior to the A.F.W curve. Similar to the observations made with ash and total sulfur rejections performances, the dense medium process provides a better separation of pyritic sulfur than the water-only process. The pyritic sulfur rejection in the dense medium Falcon process was found to be around 80%.
Figure 8. Metallurgical performance of the dense medium and water-only Falcon processes in terms of clean coal yield versus product (a) ash and (b) total sulfur for Illinois No.6 seam coal (Feed ash content = 15.5% and total sulfur content = 3.8%). Optimization data refers to dense medium Falcon process.
The optimum products obtained from the dense medium and water-only Falcon operation were subjected to sink-float analysis to evaluate the performance in terms of the separation density ($d_{50}$) and probable error ($E_p$). The partition curves obtained for the dense medium and water-only Falcon processes are shown in Figure 10. The dense medium process provided a $d_{50}$ of 1.43 with an $E_p$ value of 0.038 for the 16 x 325 mesh particle size fraction of Illinois No. 6 seam coal. Typical $E_p$ values achieved for fine coal cleaning in dense medium cyclones are above 0.075. The lower $E_p$ value for the dense medium Falcon unit reflects an improvement in current fine coal cleaning efficiencies. The higher centrifugal acceleration provided in the enhanced gravity separation (300 “g” against 60 “g” achieved in cyclone) improves the sharpness of separation. Another interesting aspect noted from these partition curves is the lower density cut point achieved in water-only Falcon Concentrator as compared to results of previous studies. The results of earlier ICCI projects indicate that the water-only Falcon could achieve $d_{50}$ of 1.6 with an $E_p$ value of 0.12. The current investigation shows that even lower $d_{50}$ values are achievable, i.e., 1.48 with an $E_p$ value of 0.105 was achieved in the water-only Falcon process. This significant improvement in the water-only Falcon process can be attributed to the better control of underflow rate achieved recently with the modified underflow nozzle design. The new underflow nozzles with the variable diameter provide uniform underflow rates unlike the opening and closing time method used in earlier models.
The experimental results obtained from the treatment of Coal No. 2 using the dense medium and water-only Falcon processes are compared in Figure 11 in terms of clean coal yield as a function of product ash and total sulfur contents. The dense medium process provided a clean coal yield of 78.9% with product ash and total sulfur contents of 5.7% and 1.5%, respectively, from a feed containing 17.5% ash and 1.5% total sulfur. The pyritic sulfur was reduced to 0.15% from 0.6%. At comparable product quality levels, the clean coal yield achieved in the water-only Falcon process was 71.2%, i.e., an improvement of 7.8% in clean coal yield due to the application of the dense medium in the enhanced gravity separation. The results also indicate the benefit of the dense medium enhanced gravity separation over flotation processes while producing high quality product with low ash contents. A significant increase in clean coal yield was realized in the dense medium process for products having lower than 4% ash content. For example, a product with 4.0% ash content and 64.9% clean coal yield was achieved in the dense medium Falcon compared to the A.F.W. curve which yielded 42.1% of the feed to the product stream.
Figure 11. Metallurgical performance of the dense medium and water-only Falcon processes in terms of clean coal yield versus product (a) ash and (b) total sulfur for Illinois No.6 seam coal (Feed ash content = 17.5% and total sulfur content = 1.5%).
Coal No. 3 – Illinois No. 5 seam middling sample

A sample from the middling stream of a spiral circuit treating Illinois No. 5 seam coal was also used to evaluate the performance of dense medium Falcon process. The middling stream is currently discarded and characterized as “difficult-to-clean” material. The feed washability analysis indicated that the coal sample contained about 36% near gravity material around the specific gravity of 1.4. Larger amount of near gravity material in the feed results in higher misplacement of middling particles and reduces the sharpness of the separation process.

Experiments were conducted on the dense medium and water-only Falcon processes using 16 x 325 mesh particle size fraction of the Illinois No. 5 middling sample as feed material. The metallurgical performance achieved using the dense medium and water-only enhanced gravity separation is shown in Figure 12. The dense medium Falcon process gave a clean coal product of 7.5% ash and 1.6% total sulfur with a yield of 62.5%. The feed ash and total sulfur contents were 22.5% and 2.5%, respectively. The pyritic sulfur content was reduced to 0.44% from 1.65%, which equates to 83.7% rejection. The partition curve obtained for the performance of the dense medium Falcon process treating the middling sample is shown in Figure 13. It is evident from the partition curve that despite the difficult feed washability characteristics, the dense medium process performed well resulting in an $E_p$ value of 0.048 at a density cut point of 1.43.

The water-only Falcon process gave 45.8% clean coal yield with ash and total sulfur contents of 7.8% and 1.6%, respectively. The dense medium Falcon process provided 16.7% mass unit increase in clean coal yield over the water-only Falcon process. The significant improvement in clean coal yield at same product quality levels is due to efficient treatment of near gravity material in the dense medium process. It was also noted that the dense medium process could produce high quality products i.e., low ash content, with reasonable clean coal yields. For example, a product of 4.5% ash content with 49.7% yield was achieved in dense medium process where it was not possible to reduce the product ash below 7.2% in the water-only Falcon process. The partition curve for the water-only Falcon process treating the middling sample is shown in Figure 8. The density cut point and probable error values estimated for the water-only Falcon process treating the middling sample was 1.56 and 0.128, respectively.

Coal No. 4 – Illinois No. 5 seam middling sample

To ascertain the performance evaluation of dense medium Falcon process, another middling sample was treated. This middling sample was even more difficult-to-clean with the feed ash and total sulfur contents of 29% and 2.7%, respectively. Experiments were conducted both on dense medium and water-only Falcon Concentrator. A series of spirals tests was also conducted to compare the dense medium and water-only enhanced gravity separation processes with the conventional fine coal cleaning unit operation.
Figure 12. Metallurgical performance of the dense medium and water-only Falcon processes in terms of clean coal yield versus product (a) ash and (b) total sulfur for Illinois No.5 seam middling sample (Feed ash = 22.3% and total sulfur = 2.5%).
The metallurgical performances in terms of clean coal yield versus product ash and total sulfur for the all three processes are presented in Figure 14. The results show the inability of conventional spirals to reduce the product ash content below 18.7%. This is due to the fact that achieving density cut points below 1.8 is generally difficult in spiral operations. The water-only Falcon process achieved a product with 8.1% ash content and clean coal yield of 32.8%. The product total and pyritic sulfur contents were 1.5% and 0.8% respectively. At comparable product quality levels, the dense medium process gave a clean coal yield of 49.1%. The spiral also could not reduce the total and pyritic sulfur contents below 2.3% and 1.3%, respectively. Around a product ash content of 18.9%, the clean coal yields achieved in dense medium, water-only and spiral processes were 73.5%, 65% and 61.9%, respectively. The performances of all three processes were found to be close at very high product ash contents due to the fact that, at high density cut points, process efficiency does not matter since relatively little near gravity material exists.

The partition curves obtained from the dense medium and water-only Falcon processes are shown in Figure 15. The dense medium and water-only Falcon processes provided $d_{50}$ and $E_p$ values of 1.49, 0.055 and 1.56, 0.178, respectively, whereas the spiral showed a $d_{50}$ of 1.9 with an $E_p$ value of 0.193. A large amount of near gravity material in the feed caused a significant reduction in the process efficiency of the water-only Falcon and spiral processes.
Figure 14. Metallurgical performance of the dense medium, water-only Falcon and spiral processes in terms of clean coal yield versus product (a) ash and (b) total sulfur for Illinois No.5 seam middling sample (Feed ash = 22.3% and total sulfur = 2.5%).
Figure 15. Partition curves obtained for the performances of the dense medium and water-only Falcon processes treating Illinois No. 5 seam middling sample.

Studies on Medium Properties and Recovery

The particle size distribution of the dense medium has significant effect on the process performance of conventional dense medium operations. Fine magnetite provides more stable suspension leading to better process efficiency. However, recovery of fine magnetite is difficult and results in high media loss. To study the effect of magnetite size distribution, experiments were conducted on the dense medium Falcon using a fine ($d_{80} = 17$ microns) and coarse ($d_{80}= 31$ microns) magnetite for treating Coal 4. The process efficiencies were analyzed in terms partition curves for the separation performance and the results are shown in Figure 16. It is evident from the results that the process efficiency is not affected by the use of coarser magnetite.

The success of the dense medium enhanced gravity separation process requires an efficient dense medium recovery. Though there are many detailed studies on dense medium fine coal cleaning and medium recovery data available in literature, preliminary tests were conducted to estimate the expected medium loss in dense medium Falcon process. For the media recovery studies the products of the dense medium tests with fine magnetite was used, as the media loss would be higher. The media recovery studies were conducted at the Eriez Magnetics laboratory by the principal investigator. Conventional wet magnetic drum separator with a variable current magnet to achieve different levels of magnetic field was
used for the tests. A Davis tube magnetic separator was used to evaluate the magnetic contents of the different streams obtained from the media recovery circuit.

A rougher-cleaner-scavenger circuit was adapted to maximize the recovery of magnetite. Three different tests were conducted using different strength of magnetic fields. Figure 17 shows the optimum results obtained from these studies which indicate 99.7% recovery of magnetite. The media loss is generally expressed in terms of weight of medium lost per ton of raw coal treated. The estimated medium loss, 3 kg/ton of raw coal treated, is higher than that of conventional dense medium coarse coal circuit, which is between 0.5 to 1.5 kg/ton of raw coal treated. Use of coarse magnetite will be a suitable alternate to further reduce the loss without affecting the process efficiency of dense medium Falcon operation.

Overall Plant Simulation and Preliminary Economic Analysis

A computer simulation of a coal preparation plant treating Illinois No. 5 seam coal was conducted to estimate overall plant performance improvement that can be achieved by replacing conventional fine coal cleaning circuit with dense medium Falcon process. The plant performance data and simulation model were obtained from the previous ICCI

Figure 16. Effect of magnetite size distribution on the separation performance of the dense medium Falcon process.
project investigation. The coal preparation plant treating the Illinois No. 5 seam coal has an annual throughput capacity of approximately 6 million clean coal tons. The operation is a four-circuit plant utilizing heavy media vessels, heavy media cyclones, spiral concentrators and conventional flotation cells. The fine coal fraction (-16 mesh), which constituted about 13% of the plant feed, is treated by spiral and conventional flotation cells.

![Figure 17. Results obtained from the optimum media recovery circuit.](image)

The performance of the optimized conventional plant and an advanced circuit with the dense medium Falcon replacing spiral circuit were simulated. Particle size-by-size partition data of different unit operations were used for the plant simulation of different circuits. The optimization of the plant was achieved by maximization of the overall plant clean coal yield for a given product quality constraint. Optimization of the overall mass yield was achieved by the equalization of incremental product grades from all the individual circuits. The improvement in clean coal yield predicted for the overall plant due to dense medium enhanced gravity separation is shown in Figures 18 (a) and (b). At the current target product ash content of 8%, the optimized conventional plant gave 76.9% yield while the dense medium circuit showed a clean coal yield of 81%. The superior separation performance achieved in dense medium process for the 16 x 325 mesh particle size fraction results in 4.1% increase in clean coal yield.
Figure 18. Predicted improvement in (a) clean coal yield and (b) incremental clean coal yield for optimized plant with the existing cleaning circuits and the dense medium Falcon (D.M.F) circuit for the treatment of Illinois No. 5 seam coal. The spiral circuit was replaced by dense medium Falcon Concentrator. Illinois No. 5 plant feed ash = 22.5%.
Figure 19. Predicted improvement in (a) annual income and (b) incremental increase in annual income for optimized plant with the existing cleaning circuits and the and the dense medium Falcon (D.M.F) circuit for the treatment of Illinois No. 5 seam coal. The spiral circuit was replaced by dense medium Falcon Concentrator. Illinois No. 5 plant feed ash =22.5 %.
Using the clean coal yield values of the optimized plant and advanced circuits obtained from computer simulations, a detailed economic analysis was conducted. The annual income of the optimized conventional plant and dense medium Falcon (D.M.F) circuit are shown in Figure 19 (a). The incremental annual income due to dense medium Falcon process over the optimized conventional plant is shown in Figure 19 (b). At the current product quality, the dense medium Falcon provided a significant additional annual income of $4.2 million after discounting the annualized differential capital cost for a depreciation period of 10 years and an annual rate of return of 12%.

Conclusions and Recommendations

Conclusions

Based on the work performed in this investigation, the conclusions can be summarized as follows:

1. Use of dense medium provided a consistently superior performance to that of water-only processes resulting in 7.8% and 17% increase in the clean coal yield for easy-to-clean coals and difficult-to-clean middlings samples respectively.

2. Organic efficiencies of up to 99% and 91% are achievable using the dense medium Falcon concentrator for easy-to-clean coals and difficult-to-clean middlings samples, respectively.

3. A specific gravity cut-point of 1.43 was achieved with a corresponding $E_p$ value of 0.038 as compared to values of about 0.08 obtained using conventional dense medium cyclones.

4. A wide range of specific gravity cut-points is possible with the dense medium Falcon concentrator without changing the feed medium density.

5. Consistent superior performance was observed with the Falcon concentrator (both water-only and dense medium processes) when compared with spirals at comparable product levels.

6. The Falcon concentrator allows a high degree of operational flexibility and is amenable to on-line process control to achieve optimum process efficiency.

7. The efficiency of the dense medium process was not affected by the size characteristics of the two different magnetite samples used for the experiments.

8. Media loss was estimated to be about 3 kilograms per ton of raw coal treated with the finest magnetite used in the study. A lower loss is expected from coarser magnetite, which has been shown to not effect the separation performance.
9. Both the water-only and dense medium Falcon processes produced compliance coal for Phase I of the Clean Air Act from Coals No. 2, 3 and 4. Coal 1 contained a high amount of organic sulfur with 6.67 lbs SO$_2$ /m BTU, which was reduced to 4.22 lbs SO$_2$ /m BTU in the dense medium Falcon process.

10. Simulations conducted on an existing coal preparation plant revealed that a 4.1% weight unit improvement in the overall plant clean coal yield could be realized by the replacement of conventional fine coal cleaning devices with the dense medium Falcon concentrator.

11. Economic analyses conducted on the same coal preparation plant predicted a $4.2 million increase in annual income by the introduction of dense medium enhanced gravity separation process after discounting the capital cost invested at the rate of 12%.

Recommendations

1. The effect and operating range of the dense medium Falcon process seems to vary with the feed coal characteristics. Statistically designed experiments may be conducted keeping the feed coal characteristics as a variable to quantify the complex relationship.

2. Studies conducted using a coarse magnetite ($d_{80} = 31.7$ microns) showed that the dense medium Falcon performance was not affected. Attempts may be made to use even coarser magnetite, which will improve the media recovery.

3. Since the dense medium Falcon performed very well in treating the middling sample, the recovery of refuse pond samples in dense medium Falcon needs to be investigated.

4. In-plant trials of dense medium Falcon would provide valuable information regarding the scale-up and full-scale operation.
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