The techno-economic benefits of using advanced fine coal cleaning (AFCC) technologies have been evaluated for two operating Illinois coal preparation plants treating the Illinois No. 5 and 6 seam coals. Using separation performance data collected from the plants, the overall impacts of the AFCC technologies were evaluated after optimization of the conventional coal cleaning processes. The plant treating the Illinois No. 6 seam coal utilizes conventional flotation cells for cleaning the –28 mesh particle size fraction, for which, column flotation and enhanced gravity separation were considered as the AFCC technologies for replacement purposes. In addition to these AFCC technologies, a hindered-bed classifier was evaluated for replacing the spiral-conventional flotation cell arrangement in the plant treating Illinois No. 5 coal. The analysis was based on the maximization of plant clean coal yield and overall mine profitability while ensuring all product quality constraining values (e.g., ash, sulfur and moisture contents).

Prior to the consideration of the AFCC technologies, simple optimization of the existing cleaning circuits indicated the potential for improving the plant clean coal yield by 0.79% and 1.63% weight units for the Illinois No. 6 and No. 5 plants, respectively, while maintaining the current product qualities. However, after replacing the conventional flotation cells with flotation columns and enhanced gravity separators, the maximum plant clean coal yield improvement of the Illinois No. 6 plant was 3.06% weight units. A detailed economic analysis revealed that the plant yield improvement translates to a $1.10 million increase in annual income after discounting the capital cost invested at a rate of 12%. The maximum yield improvement realized for the Illinois No. 5 processing plant, which has an annual production rate that is three times the Illinois No. 6 plant, was 4.47%. This yield improvement equates to an increase in annual profit of nearly $6.74 million. The significant improvements in clean coal yield predicted from the addition of advanced circuits in both plants are believed to be the result of the excellent ash cleaning performance of column flotation and hindered-bed classifiers. In coal containing a significant amount of fine (-100 mesh) coal pyrite and middling particles, enhanced gravity separation provides a significant economic benefit in achieving the required product grade. However, the techno-economic benefits is dependent on the feed coal characteristics and plant related parameters, which vary from site-to-site.
EXECUTIVE SUMMARY

Research projects funded by the Illinois Clean Coal Institute, the U. S. Department of Energy and other funding agencies have resulted in the development of several advanced fine coal cleaning technologies (AFCC). These technologies include flotation columns and enhanced gravity concentrators, which have been successfully commercialized into operating preparation plants. However, their acceptance by the coal industry has been limited due to the lack of a method to evaluate the impact of the technologies on the overall plant separation performance and mine profitability. The goal of this project was to determine the improvements in the efficiency of coal processing plants and mine profitability that can be provided from the use of overall optimization of the plant using AFCC technologies.

It is well understood that the liberation characteristics for a given run-of-mine coal improve with decreasing particle size, which allows the finest fractions to have a superior cleanability potential. Thus, by achieving a superior cleaning in the fine coal circuit of a coal preparation plant, a relatively high specific gravity separation in the coarse coal circuits can be tolerated, which would result in an increase in the overall plant clean coal yield. However, due to the inefficiencies of conventional fine coal cleaning technologies, superior separation performances are typically achieved from the intermediate and/or coarse circuits of a coal processing plant. To compensate for the relatively poor performance from the fine circuit, it is common practice to decrease the gravity cut-point in the coarse and intermediate circuits to achieve a given product quality, which is detrimental to the overall plant mass yield. In fact, for this reason, several coal companies have elected to forego the treatment of the minus 100 mesh size fraction, which creates an inherent inefficiency. After testing advanced technologies in the same plants, decisions have been made against the installation of the technologies due to product quality issues such as moisture, despite the fact that the technology performed well in pilot-scale demonstrations. One of the most important issues overlooked in these studies was the improvement in the overall economics. The economic benefits provided by the superior performance of AFCC technologies were not evaluated with respect to the entire plant and thus, the additional capital costs were not justified.

In this project, the benefits realized by the optimization of the overall plant using the conventional and advanced fine coal cleaning technologies have been evaluated and compared. To achieve this goal, Southern Illinois University teamed with two coal companies to obtain separation performance data from the conventional coal cleaning technologies, which were used to evaluate the effect of overall plant optimization and implementation of AFCC technologies. Plant 1, which treats the Illinois No. 6 coal seam, is a three-circuit operation using heavy media vessels, heavy media cyclones and conventional flotation cells. Plant 2 is a four-circuit plant treating the Illinois No. 5 seam coal whereby the only difference with Plant 1 is the combined use of spiral concentrators and conventional flotation cells to treat the –16 mesh size fraction. For both plants, two AFCC circuits were evaluated for their potential use as a replacement for the conventional fine coal cleaning technologies. For Plant 1, Advanced I circuit utilized
flotation columns, whereas, Advanced II circuit used both enhanced gravity concentrators and flotation columns in a rougher-cleaner arrangement to clean the –28 mesh particle size fraction. Since the fine circuit in Plant II treats a coarser particle size fraction, i.e., -16 mesh, a hindered-bed classifier was used as a rougher in both AFCC circuits.

An extensive plant sampling exercise was undertaken to obtain the relevant technical information from both plants. The particle size-by-size partition curve data needed for the gravity-circuits have been obtained by collecting samples of the feed, product and tailings from each unit operation at different specific gravity cut-points. Using the data collected, a global plant optimization was achieved through the utilization of a plant optimization model developed by the principal investigators. The goal of the optimization procedure was to maximize the plant clean coal yield as a function of incremental changes in product grade, i.e., ash, total and pyritic sulfur, and moisture contents. The general optimization approach of equalizing the incremental quality from each circuit was used to maximize the plant yield at a given overall product quality value. Based on the maximum clean coal yield values obtained considering the individual product assays as constraints, an overall clean coal yield maximization was achieved while simultaneously satisfying multiple product quality constraints, such as the ash, total sulfur and moisture contents of the clean coal product. A summarized list of improved yield values obtained from the optimization procedure is provided in Table 1.

Table 1. Improvements in the plant clean coal yield due to optimization based on individual product quality constraints and the implementation of advanced fine coal circuits for cleaning the Illinois No. 6 and No. 5 seam coals; current clean coal yields from Plant 1 and 2 are 72.3% and 76.8%, respectively.

<table>
<thead>
<tr>
<th>Constraining Variable</th>
<th>Feed Assays</th>
<th>Current Plant Target Assays</th>
<th>Increase in Plant Clean Coal Yield (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Optimized Plant</td>
<td>Advanced I</td>
</tr>
<tr>
<td>Illinois No. 6 (Plant 1)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ash</td>
<td>28.3%</td>
<td>7.44%</td>
<td>0.99</td>
</tr>
<tr>
<td>Total Sulfur</td>
<td>1.08%</td>
<td>1.08%</td>
<td>1.60</td>
</tr>
<tr>
<td>Pyritic Sulfur</td>
<td>0.57%</td>
<td>0.44%</td>
<td>0.87</td>
</tr>
<tr>
<td>Illinois No. 5 (Plant 2)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ash</td>
<td>22.4%</td>
<td>8.00%</td>
<td>1.77</td>
</tr>
<tr>
<td>Total Sulfur</td>
<td>1.40%</td>
<td>1.12%</td>
<td>1.27</td>
</tr>
<tr>
<td>Pyritic Sulfur</td>
<td>0.56%</td>
<td>0.45%</td>
<td>0.75</td>
</tr>
</tbody>
</table>

It is obvious from the Advanced I circuit data in Table 1 that the most significant increase in overall plant clean coal yield occurs on the basis of the product ash content constraint from the installation of flotation columns. For both plants, greater than 3% weight unit increase in the amount of coal recovered from the plant can be realized if product ash content is the only critical product quality constraint. However, the application of the enhanced gravity concentrator has an apparent importance in determining the overall
plant yield when pyritic sulfur rejection is a goal as indicated by the Advanced II circuit results. Although the yield improvement values associated with the pyritic sulfur constraint were significant for both plants, the impact on total sulfur content was only realized for Plant 1. It is believed that this finding is due to the difference in the relative concentrations of the organic and pyritic sulfur contents in the feed coals, i.e., the organic-to-pyritic sulfur ratio is greater in the Illinois No. 5 seam coal.

The most significant clean coal yield improvements resulting from the implementation of the AFCC technologies can be realized when all current product quality requirements are simultaneously satisfied. From a comparison of the results in Table 1 and 2, total sulfur content was found to be the most important constraint for determining potential plant yield improvements in Plant 1. The use of the enhanced gravity concentrator, which is known to provide excellent sulfur rejection, allowed an increase in plant mass yield of nearly 1.00% weight units compared to the sole use of flotation columns. However, for Plant 2, the improvement in clean coal yield is less constrained by the product sulfur content requirement. Thus, the clean coal yield difference between Advanced I and II circuits is less significant in the case of Plant II.

Table 2. Improvements in the plant clean coal yield due to optimization based on the need to simultaneously satisfy all product quality constraints and the implementation of advanced fine coal circuits for cleaning the Illinois No. 6 and No. 5 seam coals; current clean coal yields from Plant 1 and 2 are 72.3% and 76.8%, respectively.

<table>
<thead>
<tr>
<th>Constraining Variable</th>
<th>Feed Assays</th>
<th>Current Plant Target Assays</th>
<th>Increase in Plant Clean Coal Yield (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Optimized Plant</td>
<td>Advanced I</td>
</tr>
<tr>
<td>Illinois No.6 (Plant 1)</td>
<td></td>
<td>Illinois No. 6 (Plant 1)</td>
<td></td>
</tr>
<tr>
<td>Multiple Ash</td>
<td>28.3%</td>
<td>7.44%</td>
<td>0.79</td>
</tr>
<tr>
<td>Total Sulfur Moisture</td>
<td>1.08%</td>
<td>1.08%</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>11.6%</td>
<td></td>
</tr>
<tr>
<td>Illinois No. 5 (Plant 2)</td>
<td></td>
<td>Illinois No. 5 (Plant 2)</td>
<td></td>
</tr>
<tr>
<td>Multiple Ash</td>
<td>22.4%</td>
<td>8.00%</td>
<td>1.63</td>
</tr>
<tr>
<td>Total Sulfur Moisture</td>
<td>1.40%</td>
<td>1.12%</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>12.0%</td>
<td></td>
</tr>
</tbody>
</table>

Based on the predicted clean coal yield improvements, a detailed economic analysis was conducted to evaluate the increase in overall revenue and net annual income resulting from the replacement of the existing conventional fine coal circuits with the AFCC circuits. The economic analysis included the additional revenue resulting from the improved clean coal yield of the plant in the cash-inflow based on a coal-selling price of $20 per ton of clean coal. This analysis considered the base mining and processing costs.
of $10 and $3 per ton of raw coal, respectively. The annualized capital costs of the advanced fine coal technologies based on a depreciation period of 10 years and an annual rate of return of 12% have been included in the cash-outflow. Based on the economic analysis, the overall production (including mining and processing) cost as a function of incremental changes in product quality was evaluated.

A summarized list of improved annual income realized while maintaining the required product quality is provided in Table 3. Due to the difference in annual plant production and the projected improvements in clean coal yield shown in Table 2, significantly higher revenue was estimated for Plant 2. After discounting the annual capital cost, a $1.1 million revenue increase was project for Plant 1 from the implementation of the enhanced gravity and flotation column circuit (Advanced II circuit). However, for reasons previously discussed, the enhanced gravity-based circuit was not found to provide the maximum revenue improvement for Plant 2. In fact, Advanced I circuit, which utilizes hindered-bed classification and column flotation was predicted to provide the maximum increase in annual revenue of approximately $6.7 million.

Table 3. Increase in annual income due the optimization of the existing conventional plant and application of the advanced fine coal cleaning circuits for cleaning the Illinois No. 6 and No. 5 seam coal.

<table>
<thead>
<tr>
<th>Constraint Variable</th>
<th>Feed Assays</th>
<th>Current Plant Target Assays</th>
<th>Increase in Annual Income ( million $ )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Optimized Plant</td>
</tr>
<tr>
<td>Illinois No.6 (Plant 1)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Multiple Ash</td>
<td>28.3%</td>
<td>7.44%</td>
<td>0.47</td>
</tr>
<tr>
<td>Total Sulfur Moisture</td>
<td>1.08%</td>
<td>1.08%</td>
<td></td>
</tr>
<tr>
<td>Illinois No. 5 (Plant 2)</td>
<td></td>
<td></td>
<td>2.67</td>
</tr>
<tr>
<td>Multiple Ash</td>
<td>22.4%</td>
<td>8.00%</td>
<td></td>
</tr>
<tr>
<td>Total Sulfur Moisture</td>
<td>1.40%</td>
<td>1.12%</td>
<td></td>
</tr>
</tbody>
</table>

The results presented in Table 3 were based on the requirements to achieve the current product quality requirements. However, more stringent product quality requirements will necessitate the use of the most efficient AFCC circuit. The findings of this study indicate that the Advanced II circuit, which utilizes all three aforementioned AFCC technologies, provides the most efficient separation performance based on both ash and pyritic sulfur rejection. As such, the economic benefits associated with the use of the Advanced II circuit will improve as the product quality requirements become more constrained. In addition, the techno-economic benefits of all AFCC technologies/circuits are a function of the feed coal characteristics and the operating parameters of each coal processing plant.
OBJECTIVES

The overall goal of the project was to determine the improvements in coal preparation plant efficiency and overall mine profitability that can be realized from the implementation of advanced fine coal cleaning technologies and overall plant optimization. The specific project objectives were:

1. To construct a plant optimization model that will determine the optimum gravity cut-points for each conventional cleaning circuit in a processing plant to provide a given product grade at minimal process costs.

2. To evaluate the economic and technical benefits for the entire preparation plant from the use of advanced fine coal cleaning technologies by achieving highly efficient, low gravity cut-points.

The minimum processing costs for achieving an incremental improvement in product quality (i.e., ash, sulfur and moisture) was to be determined for processing plants using conventional and advanced fine coal cleaning circuits. The economic benefits of using advanced fine coal cleaning technologies were to be evaluated based on the improvements in net annual income from the entire mining operation.

INTRODUCTION AND BACKGROUND

Research sponsored by the Illinois Clean Coal Institute (ICCI) and the U. S. Department of Energy over the past decade has resulted in the commercial development of several advanced fine coal cleaning technologies. These technologies, such as enhanced gravity concentrators and column flotation, have been found to provide a high energy recovery while achieving very low ash and low sulfur content products. This ability is due to the improved process efficiencies over conventional processes and the better liberation of the associated mineral matter and pyrite in the fine coal fractions. Due to liberation problems, coarse coal particles can not be cleaned to the same level. As a result, companies using the conventional techniques typically lose substantial amount of coal when trying to achieve lower levels of ash and sulfur in their products.

For example, a coal company that receives a new contract may be required to decrease the ash content in their coal product from 10% to 9%. To achieve this goal, they will decrease the gravity cut point in their cleaning devices where feasible to achieve the 9% product. Typically, the coarse coal circuit will be operated at a lower gravity cut-point than the intermediate fraction. Since conventional fine coal cleaning devices do not allow adjustment in the gravity cut point, the coal operator may be required to decrease the gravity even lower than required to achieve the desired overall coal quality. However, for simplicity, assume that the operating parameters of the cleaning units treating each size fraction can be adjusted to achieve the 9% ash product. As shown in the Figure 1, this results in a substantial energy recovery loss in the coarse fraction for the coal in this example. However, little or no loss in recovery is obtained in the fine fraction (fine coal
curve in Figure 1 is representative of a froth flotation process without entrainment). In fact, a much lower ash content can be achieved in the fine fraction while maintaining a high recovery of combustibles. In this example, if the gravity cut point or separation performance in the fine fraction was controllable, the decrease in the overall product ash content could be achieved by reducing the ash content in the fine and intermediate circuit products to 5% and 9%, respectively, while maintaining the coarse product at its current grade (assuming 50% weight to coarse, 35% to intermediate, and 15% to fine). Thus, the reduction in product ash content would have a minimum effect on energy recovery.

The development of the advanced technologies allows the production of high quality fine coal concentrates while achieving high energy recovery values. Thus, using these technologies, a coal operator may be able to blend the high quality material with the coarse material to achieve the low ash and sulfur content products required by the contract. The obvious question is “What adjustments are needed to the entire plant to reduce an increment of ash, sulfur or trace element(s) in the product while achieving a maximum yield to the product”? This is a complicated question since the adjustments are a function of the material in each size fraction and the equipment used. The development of a methodology to provide a solution to the aforementioned optimization problem is the subject of this research project. The optimized plant yields determined from the methodology were used to evaluate the overall improvement in mine profitability that can be realized from the installation of the advanced fine coal cleaning technologies and circuits.

![Figure 1](image_url)
The plant optimization and evaluation of techno-economic benefits of advanced fine coal cleaning technologies have been conducted for two Illinois coal preparation plants. The flowsheet of the first plant treating the Illinois No. 6 seam coal is shown in Figure 2, which shows each unit operation along with the assays of each stream. The + ½ inch feed coal is treated by a primary heavy media (Teska) vessel while the ½ in x 4 mesh material is cleaned in a fine heavy media (Teska) vessel. The tailings from both the coarse and fine heavy media vessels are then combined and retreated in a secondary heavy media (Teska) vessel. The floated material from each of the heavy media vessels is combined as a final +4 mesh product. The 4 x 28 mesh particle size fraction is treated in dynawhirlpools (DWP), which are special types of heavy media centrifugal separators. Two dynawhirlpools are used in a rougher-scavenger circuit arrangement. The -28 mesh size fraction is treated in conventional flotation cells in a rougher-cleaner circuit arrangement.

The second plant that was considered in this investigation treats Illinois No. 5 seam coal. As shown in the flowsheet in Figure 3, the plant is a four circuit operation, where the +3/4” size coal is treated in heavy media vessels and 3/4” x 16 mesh particle size fraction in heavy media cyclone. The fine coal circuit consists of two unit operations, where the 16 x 100 mesh size fraction is treated in spiral concentrators and the –100 mesh size fraction is cleaned using conventional flotation cells. The advanced fine circuits evaluated for both plants are combinations of hindered bed classifiers, enhanced gravity separators and flotation columns as shown in Figure 4. The Advanced I circuit consists of flotation columns and a combination of hindered bed classifiers and flotation columns for the plants 1 and 2, respectively. On the other hand, the Advanced II circuit includes enhanced gravity separators-flotation columns and hindered bed classifiers-enhanced gravity separators-flotation columns, respectively.

An extensive sampling exercise was conducted in the plants to obtain the feed washability information for each particle size fraction along with a detailed analysis of the separation performances achieved by the individual unit processes in the two coal preparation plants. Based on the analysis of the samples obtained at various settings of the gravity separators, a functional relationship was developed between cut density (d_{50}) and probable error (E_P) for each unit operation on a particle size-by-size basis. These relationships have been used in a plant simulation model to optimize the overall plant performance. It may be noted that, since the actual plant performance data have been used in the simulations, more realistic predictions are expected from the plant optimization model.

**Simulation Methodology**

As shown in Figure 5 (a), the primary input required by the model for the simulation of plant performance is the detailed size-by-size washability data of the feed coal. The run-of-mine coal is screened into different size fractions and cleaned in different circuits. A
Figure 2. Current flowsheet the coal processing plant (Plant 1) treating run-of-mine Illinois No. 6 seam coal.
Figure 3. Current flowsheet the coal processing plant (Plant 2) treating run-of-mine Illinois No. 5 seam coal.
Figure 4. Proposed Advanced Fine Coal Cleaning Circuits I and II, respectively, for the preparation plants treating Illinois No. 6 (a, b) and Illinois No. 5 (c, d) seam coals.
Figure 5  The step-by-step methodologies used for (a) the plant simulation and (b) the optimization strategy utilized in the present investigation.
screening model with an exponential form of the equation incorporating appropriate screen efficiencies and shape factors was used to estimate the actual feed characteristics reporting to each cleaning circuit. The partition numbers, which represent the probability of a particle of a specific density to report to the product stream, were generated using Whiten’s model and the respective separator inefficiencies \( E_p \). The probable error \( E_p \) values were obtained by fitting the appropriate constant values using the original plant data to the well established empirical equations available in literature describing \( E_p \) values as a function of the density cut point being achieved in the separator and the size of the particles. Individual circuit clean coal yield versus product grade relationships were thus obtained from the partition numbers and the feed washability data. These relationships were used to generate the clean coal yield versus product incremental grade curves for the individual circuits.

The optimization of the plant was achieved by maximization of the overall plant clean coal yield for a given product grade constraint. These constraints included the product grades such as ash, total sulfur, pyritic sulfur, moisture and trace element contents individually or simultaneously. Since the trace element data for the Illinois No. 5 coal seams were not available, the optimization exercise based on the individual trace element constraints were conducted only for the plant treating the Illinois No. 6 seam coal. Optimization of the overall mass yield was achieved by the equalization of incremental product grades from all the individual circuits. This was achieved by a step-by-step procedure depicted by the flowchart in Figure 5 (b). Search for the optimal incremental product grade for maximizing the overall plant yield was initiated from a very high incremental ash value. Individual circuit yields were calculated for the same product incremental ash for all the cleaning circuits from their respective clean coal yield versus product incremental grade curves. Corresponding product grade values were obtained for the circuit yields from their respective clean coal yield versus product grade curves. The individual clean coal yields and product grades were combined in the proportion of the weight fractions being treated by the individual circuits to obtain the overall plant clean coal yield and product grades. If any of the product grades did not fall under the specifications or the constraints as determined by contractual obligations, the procedure was repeated for a lower incremental product grade until all product quality requirements were achieved. Using this methodology, the overall plant clean coal yield represents the maximum achievable yield from the existing plant for all product quality constraints.

The separation performances of the advanced cleaning technologies considered in this study were obtained from previous ICCI investigations. The partition curves for the hindered-bed classifier originated from a study of the Floatex Density separator, which was evaluated in an operating coal preparation plant. The flotation column performance was estimated from advanced flotation washability data, which can be achieved in a single cleaning stage using the Packed-Column technology. The partition curves for the enhanced gravity concentrator were obtained from an earlier study on the C40 Falcon Concentrator, which has a throughput capacity greater than 75 tons per hour.
RESULTS AND DISCUSSION

Plant 1: Preparation Plant Treating Illinois No. 6 Seam Coal

The coal preparation plant treating approximately 3 million tons of raw Illinois No. 6 coal annually is a three-circuit plant with heavy media vessels, dynawhirlpools and conventional flotation cells. Using the metallurgical performance data obtained from the operating plant and the aforementioned plant optimization model, the plant performance was optimized for the aforementioned different scenarios. Initially optimization was conducted with single constraining variable, such as ash, total sulfur and moisture contents. The final optimized clean coal yield value on the basis of all the important constraints considered simultaneously was obtained from the individual optimum values by pursuing an iterative procedure.

Product Ash Constraint: The plant performance optimization conducted equalizing the incremental ash from each cleaning circuit indicates that the plant clean coal yield can be improved by mere optimization of the cleaning circuits. As shown in Figures 6 (a) and (b), at the current target product ash level of 7.44%, plant optimization with the existing conventional circuits predicted about 1% increase in clean coal yield. By replacing the conventional flotation cells by the flotation columns (i.e., the Advanced I configuration) would result in additional 2.22% improvement in clean coal yield while addition of enhanced gravity separator (i.e., Advance II configuration) only provided a marginal increase in yield by 0.2% over that of the Advanced I circuit. These findings are the result of superior ash cleaning achieved by column flotation for the fine coal, which allows higher density cut points for coarser fractions resulting in significant overall improvement in clean coal yield. Addition of enhanced gravity separator in the fine coal cleaning circuit with column flotation only provides marginal increase in yield, which suggests that column flotation provides near optimum separation of ash material and further improvement in ash cleaning is difficult to achieve using the enhanced gravity separator.

It may also be noted that at lower target product ash levels the advanced fine coal cleaning circuits show significant increase in clean coal yield. For example, at a product ash content of 5%, the Advanced I circuit would provide 4.43% higher yield over the optimized plant with the existing circuits. It is also noted that the plant optimization does not significantly increase the mass yield at lower product ash levels. This trend is a result of the limitations with the conventional cleaning technologies utilized in the fine coal circuits. The conventional flotation cells do not efficiently treat the clay mineral particles and the middling particles, which is necessary to achieve low ash products from the fine circuits. On the other hand, flotation columns operated with a deep froth zone provide more selective flotation environment and hence there exists a large difference in clean coal yield between optimized plant with existing units and advanced circuits at lower product ash levels as shown in Figures 6 (a) and (b).
Figure 6. Predicted improvement in (a) clean coal yield and (b) incremental clean coal yield on the basis of product ash content for optimized plant with the existing cleaning circuits and the advanced cleaning circuits for the treatment of Illinois No. 6 seam coal. The advanced circuit I replaces the conventional flotation with column flotation while advanced circuit II replaces conventional flotation with enhanced gravity separation and column flotation. Illinois No. 6 plant feed ash = 27.4%.
**Product Sulfur Constraint:** Considering product total sulfur and pyritic sulfur contents as the constraining variables, computer simulations have been conducted to optimize the existing plant operation and evaluate the enhanced performance achievable by utilizing advanced fine coal cleaning circuits. In this approach, the incremental sulfur content from each circuit was equalized to obtain the maximum clean coal yield value at a given product sulfur content. The predicted improvements in clean coal yield with optimized plant and advanced circuits are shown in Figures 7 (b). The results of computer simulation indicated that the plant optimization with existing unit operations would provide 1.6% improvement in clean coal yield while satisfying the current target product total sulfur content of 1.08%. The actual improvement in clean coal yield after optimization was due to the allowance of a greater product total sulfur content from the conventional flotation circuit while the total sulfur content produced from the coarse heavy media vessel was reduced. This allowed a substantially higher clean coal yield to be achieved from the conventional flotation cells, which resulted in a 1.6% weight unit improvement in mass yield. The corresponding improvement in plant yield value on the basis of the pyritic sulfur constraint was 1.8% as shown in Figure 7 (a).

The replacement of the conventional flotation cells with the Advanced II circuit including an enhanced gravity separator resulted in a significant increase in the clean coal yield evaluated both with pyritic and total sulfur constraints. The respective improvements in yield values were 2.42% and 3.82%, which was a result of the superior sulfur cleaning performance of the enhanced gravity separators. The yield improvements were as high as 4% and 5%, respectively at lower product sulfur levels. The improvement in plant yield at a given sulfur content due to the Advanced I circuit, which uses a flotation column was only marginal due to a relatively inferior sulfur cleaning ability of flotation columns.

**Multiple Constraints:** A coal preparation company has to normally comply with more than one product quality. In general, product ash, total sulfur and moisture contents have to be maintained below certain contractual limits. Such limits for Plant 1 are 7.44% ash, 1.08% sulfur and 11.6% moisture. Computer simulations have been conducted at different multiple constraint levels to evaluate the benefits of plant optimization with conventional and advanced fine coal cleaning circuits.

These simulations resulted in an important finding that the implementation of the advanced fine coal circuits results in only a marginal increase in product moisture content (< 0.5%). This is due to the fact that the increased amount of moisture from fine coal circuit is counter-balanced in the overall plant product due to a significant increase in clean coal yield from the coarse circuits, which contain relatively low moisture.

The predicted improvements in clean coal yield obtained from the optimization of the plant with and without the advanced fine coal cleaning circuits are shown in Figures 8 (a) and (b). These figures indicate that plant optimization with the conventional technologies would result in a 0.79% increase in the overall clean coal yield, while satisfying the current contractual grade of 7.44% ash, 1.08% total sulfur and 11.6%
Figure 7. Predicted improvement in (a) clean coal yield and (b) incremental clean coal yield on the basis of product sulfur content for optimized plant with the existing cleaning circuits and the advanced cleaning circuits for the treatment of Illinois No.6 seam coal. The advanced circuit I replaces conventional flotation with column flotation while advanced circuit II replaces conventional flotation with enhanced gravity separation and column flotation. Plant feed sulfur = 1.08%, pyritic sulfur: 0.57%
Figure 8. Predicted improvement in (a) clean coal yield and (b) incremental clean coal yield on the basis of multiple constraints for optimized plant with the existing cleaning circuits and the advanced cleaning circuits for the treatment of Illinois No. 6 seam coal. The Advanced I circuit replaces conventional flotation with column flotation while the Advanced II circuit replaces conventional flotation with enhanced gravity separation and flotation columns. Feed ash = 27.4% and feed total sulfur = 1.08%.
moisture. The additional improvements in clean coal yield with Advanced I and II circuits are 1.28% and 2.27%, respectively. These results clearly show the superior ash and sulfur rejection provided by the enhanced gravity-flotation column combination in the Advanced II circuit. The improvement in clean coal yield is even higher at lower product ash and sulfur content levels.

**Plant 2: Preparation Plant Treating Illinois No. 5 Seam Coal**

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. The two advanced fine circuits that were evaluated to replace the existing conventional circuit are combinations of a hindered bed classifier-flotation column and hindered bed classifier-enhanced gravity separator-flotation column, respectively. The 16 x 48 mesh fraction was proposed to be treated by the hindered bed classifier, whereas the –48 mesh fraction was to be treated by flotation columns or a combination of enhanced gravity separators and flotation columns in a rougher-cleaner arrangement. The performance enhancements that were predicted from the simulation exercise using the original plant data on the existing circuits and the past data of the principal investigators obtained from the individual advanced fine coal cleaning technologies are discussed in the following section.

**Product Ash Constraint** : Figures 9 (a) and (b) show the clean coal yield improvements projected from the optimization of the existing conventional coal cleaning circuits and the preparation plant after installation of the AFCC circuits. The plant, which currently achieves a yield to product of about 76.8%, can achieve a 1.77% improvement in clean coal yield at the current target product ash content of 8.0% after simple optimization. Use of the Advanced I circuit, which uses a combination of hindered bed classifiers and flotation columns in place of spirals and conventional flotation cells, resulted in 4.53% improvement in clean coal yield while the addition of enhanced gravity separator only provided an additional marginal increase of 0.1%. These findings are the results of the superior ash cleaning performance achieved by the combination of hindered bed classifier and flotation columns for treating the –16 mesh particle size fractions.

As previously discussed, the addition of the enhanced gravity separator in the fine coal cleaning circuit with column flotation only provides a marginal increase in the clean coal yield due to the fact that column flotation provides near optimum separation of ash material. Hence, further improvements caused by the enhanced gravity separator are not substantial. The benefits of advanced circuits have been found to be higher at low product ash levels similar to the results obtained with Plant 1. For example, at a 4.5% product ash content, the increase in clean coal yield due to Advanced I and II circuits are 4.95% and 5.52%, respectively.
Figure 9. Predicted improvement in (a) clean coal yield and (b) incremental clean coal yield on the basis of product ash content for optimized plant with the existing cleaning circuits and the advanced cleaning circuits for the treatment of Illinois No. 5 seam coal. The spiral and conventional flotation cell are replaced by hindered bed classifier and column flotation in advanced circuit I whereas hindered bed classifier-enhanced gravity separator-flotation column arrangement is used in Advanced II circuit. Illinois No. 5 plant feed ash =22.47%.
Product Sulfur Constraint: Considering the product pyritic sulfur and total sulfur contents as the constraining variables, computer simulations have been conducted to optimize the existing plant operation and evaluate the performance enhancement achievable using the advanced fine coal cleaning circuits. The predicted improvements in clean coal yield with the optimized conventional plant and advanced circuits are shown in Figures 10 (a) and (b). The plant optimization based on the constant incremental total sulfur approach provided 1.27% improvement in clean coal yield while achieving current target product total sulfur of 1.12%. The Advanced circuit I, which replaces spirals and conventional flotation cells with hindered bed classifiers and flotation columns would result in 2.26% increase in yield. This finding is result of better sulfur rejection achieved in hindered bed classifier than the existing spiral circuit. However, Advanced circuit II, which included the enhanced gravity separator, provided only a 0.23% increase in clean coal yield over the Advanced I circuit at the present target product sulfur level. This may be occurring due to the fact that the feed sulfur is concentrated in the 16 x 48 mesh particle size fraction, which is efficiently treated in the hindered bed classifier. Since the sulfur content of the minus 48 mesh size fraction is relatively small, the role of the enhanced gravity separator (EGS) to provide a substantial performance improvement is limited. However, at lower target product sulfur levels, the advanced circuit II using an EGS shows significant improvement in clean coal yield over the Advanced I circuit. For example at a 0.96% product total sulfur level, the Advanced II circuit provided a 6% greater clean coal yield value when compared to that obtained from the Advanced I circuit. The clean coal yield evaluated on the basis of product pyritic sulfur shows significant improvement for the Advanced II configuration because of the superior pyritic sulfur rejection performance achievable from the enhanced gravity separators.

Multiple Constraints: For Plant 2, the contractual target product qualities were 8% ash, 1.12% total sulfur and 12% moisture. Plant simulations were conducted while simultaneously maintaining the product ash, total sulfur and moisture contents as constraints to evaluate the benefits of optimizing the existing circuits and the Advanced I and II circuits.

As shown in Figure 11, the plant optimization provided a 1.63% increase in clean coal yield at the current target product quality. By using the Advanced I circuit to treat the minus 16 mesh particle size fraction, an increase in clean coal yield of 4.53% was predicted. The Advanced II circuit, which adds an enhanced gravity separator to the Advanced I circuit, resulted in a relatively insignificant improvement of 0.07% in clean coal yield over the Advanced circuit I. It should be noted that the fine coal fraction in the feed coal contains low sulfur for which the product ash became the limiting factor in the evaluation based on multiple constraints and, hence, the addition of the EGS did not show any significant improvement in clean coal yield.
Figure 10. Predicted improvement in (a) clean coal yield and (b) incremental clean coal yield on the basis of product total sulfur content for optimized plant with the existing cleaning circuits and the advanced cleaning circuits for the treatment of Illinois No. 5 seam coal. The spiral and conventional flotation cells are replaced by hindered bed classifier and column flotation in advanced circuit I whereas hindered bed classifier-enhanced gravity concentrator-column flotation arrangement is used in Advanced circuit II. Illinois No. 5 plant feed total sulfur = 1.40\%, pyritic sulfur = 0.56\%. 
Figure 11. Predicted improvements in (a) clean coal yield and (b) incremental clean coal yield on the basis of multiple constraints for optimized plant with the existing cleaning circuits and the advanced cleaning circuits for the treatment of Illinois No. 5 seam coal. The spiral and conventional flotation cells are replaced by hindered bed classifiers and flotation columns in Advanced I circuit whereas a hindered bed classifier-enhanced gravity concentrator-flotation column arrangement is used in the Advanced II circuit. Illinois No. 5 plant feed ash = 22.47% and total sulfur = 1.40 %.
Based on the predicted improvement in clean coal yield values and the additional capital investment necessary for replacing the conventional fine coal cleaning circuits with several advanced fine coal cleaning technologies, a detailed economic analysis was conducted to evaluate the resulting overall mine profitability. The evaluation of the economic benefits is described in the following section.

Economic Analysis

Using the clean coal yield values of the optimized plant and advanced circuits obtained from computer simulations, a detailed economic analysis was conducted in two phases. The incremental cost of producing clean coal is calculated in the first phase, whereas the incremental annual income for the optimized plant and advanced circuits were estimated in the second phase. The calculations were performed using an EXCEL spreadsheet model, in which an option was provided to select the mode adding an advanced fine coal cleaning circuit (AFCCC) to the existing plant. This addition can be totally new for a plant that does not have a fine coal cleaning circuit, or for plants that has conventional fine coal cleaning circuits, in which case, the differential capital cost is taken into account.

A simplified flowchart explaining the major steps involved in economic analysis is shown in Figure 12. The necessary engineering and financial information to estimate the incremental cost of producing clean coal in the optimized conventional plant and advanced circuits were obtained from the coal companies, plant designers and equipment manufacturers. This analysis considered the base level mining and processing costs of $10 and $3 per ton of raw coal, respectively, and a selling price of $20 per ton of clean coal. The differential capital cost was annualized based on a depreciation period of 10 years and an annual rate of return of 12%. A detailed description of the economic analysis is presented in Appendix I.

Plant 1

The economic analysis conducted in the aforementioned fashion using the simulated plant performance based on multiple constraints indicates that the current annual income from the Mine 1 is approximately $4 million. As shown in Figures 13 (a) and (b), an optimized plant with the existing cleaning technologies would increase the annual income by about $0.47 million, while achieving the current target grades. The Advanced circuits I and II would increase the annual income by $0.97 million and $1.10 million, respectively. It should be noted that the advanced circuit II provided the maximum economic gain over the entire range of multiple constraint values checked in spite of the maximum capital investment necessary for this option.
Figure 12 Simplified flowchart of economic analysis model used in this investigation to evaluate the financial benefits of plant optimization and advanced fine coal cleaning circuits.
Figure 13. Predicted (a) annual income and (b) increase in annual income on the basis of multiple constraints for the optimized plant with the existing cleaning circuits and the advanced cleaning circuits for the treatment of Illinois No. 6 seam coal. The Advanced I circuit replaces conventional flotation with column flotation while Advanced II circuit replaces conventional flotation with enhanced gravity separators and flotation columns. Feed ash = 27.4% and feed sulfur = 1.08%.
Plant 2

The annual income from the Mine 2 producing approximately 6 million tons of clean coal per year is about $20 million satisfying the present target grades as shown in Figure 14 (a). The economic analysis based on the simulation results obtained considering the multiple constraints indicate that an improvement of about $2.67 million in annual income can result from optimizing the plant with the existing cleaning units. The additional economic benefits obtained due to the installation of the Advanced circuits I and II were approximately $4.07 and $3.98 million, respectively. These significantly high improvements in the mine profitability clearly justify the installation of the advanced fine coal cleaning circuits.

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

1. A significant improvement in mine profitability was predicted from the improved plant clean coal yield values resulting from the replacement of conventional fine coal cleaning technologies with advanced technologies. This finding was obtained based on the current product grade requirements of two Illinois coal preparation plants. For the plant treating Illinois No. 5 seam coal, the use of a fine coal circuit employing hindered-bed classification and column flotation was found to provide an increase in annual revenue of about $6.7 million after discounting the capital cost of the advanced technologies. The application of enhanced gravity separation and column flotation was also found to increase the annual profit of an Illinois mining operation extracting Illinois No. 6 seam coal. The increase in annual profit was estimated to be approximately $1.0 million, which is smaller than the Illinois No. 5 coal plant due to lower yield improvements and annual production rates.

2. For both processing plants, optimization of the existing conventional coal cleaning circuits using a constant incremental product quality approach predicted a substantial improvement in overall plant clean coal yield. The increases in incremental yield obtained while ensuring the current product quality requirements were 0.8% and 1.6% weight units for the Illinois No. 6 and No. 5 plants, respectively. This improvement could be easily realized without the need of additional capital.

3. For the coal preparation plants evaluated in this study, the greatest clean coal yield improvement was obtained from the flotation column based circuits. When considering product ash content as a sole constraint, the replacement of the conventional flotation cells with flotation columns provided a 3.5% increase in the overall plant mass yield for the Illinois No. 6 plant. Likewise, a 4.5% yield improvement was projected for the Illinois No. 5 plant when the column flotation was used in conjunction with hindered-bed classification. At the current product quality values, the use of enhanced gravity concentration was not found to provide a significant improvement beyond that of the column-based circuit for the Illinois No. 5
Figure 14. Predicted improvement in (a) annual income and (b) incremental increase in annual income on the basis of multiple constraints for optimized plant with the existing cleaning circuits and the advanced cleaning circuits for the treatment of Illinois No. 5 seam coal. The spiral and conventional flotation cells are replaced by hindered bed classifier and column flotation in advanced circuit I whereas hindered bed-enhanced gravity separator-column flotation arrangement is used in advanced circuit II. Plant feed ash =22.47% and total sulfur = 1.14%.
coal plant. This finding is likely a result of the relatively small amounts of middling particles in both the seam coals evaluated in this study.

4. In contrast to the findings associated with product ash content constraints, enhanced gravity separation was found to provide significant advantages when pyritic sulfur content was considered as a constraint. This is likely due to the floatability of the coal pyrite. In comparison to the column-based circuit, the enhanced gravity-based system provided greater than 3% improvement in plant clean coal yield.

5. The plant simulation results indicate that more stringent product quality requirements will necessitate a more efficient fine coal cleaning system to maintain profitability. The most efficient circuit evaluated in this study incorporated the use of all three aforementioned AFCC technologies in a circuitry arrangement. This circuit maintained profitability at the lowest values of product ash and total sulfur contents. In addition, the two coal sources evaluated in this study contained relatively small amounts of middling particles. For coals containing a higher quantity of middling particles in the fine particle size fractions, high efficiency fine coal cleaning will be required to maintain overall mine profitability.

Recommendations

1. A lack of information exists on the effects of product quality and overall composition of the fine particle size fractions on the final moisture contents of the coal concentrate after treatment in a dewatering process. This information is required to gain a realistic assessment of the moisture constraint and, thus, the overall profitability of the fine coal cleaning circuit.

2. A similar analysis to that conducted on the two preparation plants in this study needs to be performed on other mine operations in the Illinois Coal Basin to evaluate overall potential of the AFCC technologies for improving the net revenue gained from the state’s natural resource base. The coals evaluated in this study can be classified as relatively easy-to-clean. It is believed that more significant benefits of the AFCC technologies will be realized at other Illinois coal mining operations.
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