ABSTRACT

It is well understood that the high cost of producing coal is a more significant parameter than the high sulfur content when considering the declining trend in Illinois coal sales. Hence, the reversal of this trend will require stringent cost cutting measures in all relevant cost components, including the coal preparation cost. One way to reduce coal preparation cost, which is expressed on the basis of cost per ton of clean coal, is to increase the amount of clean coal recovered from a given amount of raw coal without adding to the total cost incurred in the preparation of that coal.

The main objective of this project was to develop a plant optimization model to maximize the clean coal yield from an operating plant while satisfying the multiple product quality constraints, such as upper limits on ash, sulfur and moisture contents. An innovative approach using genetic algorithms (GA) was utilized for the first time to maximize the plant yield while satisfying multiple product quality constraints. The continuous parameter GA approach was used for the optimization process for which a suitable objective function was developed by simultaneously considering the overall plant yield and the individual quality constraints. The coal preparation plant that participated in this study belongs to the American Coal Company’s Galatia Mine. The hostplant treats 2,100 tph of raw coal to produce mass yields of 52.1% and 58.0% for two different blends of raw coal while satisfying the product quality constraints of 6.75% ash, 1.20% sulfur and 13,600 Btu/lb of heating value. A detailed plant sampling program was conducted for each unit operation, including heavy media vessel, heavy media cyclone, spirals and flotation banks, operating in the plant to generate input data for the optimization model. The maximum plant yield achieved by the plant optimization model developed using genetic algorithms was 54.6% and 59.2% for the two coal blends while satisfying the aforementioned product quality constraints. A minimum increase of nearly 1.2% in the overall plant yield for the Galatia plant may translate to increased production of more than 20 tph of clean coal and over $2 million in annual revenue.
EXECUTIVE SUMMARY

Numerous studies (Salama, 1986, 1991; Lyman, 1992; Rong, 1992; Sen et al., 1994; Honaker et al., 1997) have been conducted in the past to develop a suitable procedure to maximize the overall plant yield while satisfying a desired product quality. The recommended necessary condition for maximizing the overall plant yield is to equalize the incremental (or elemental) product quality from each circuit in contrast to equalizing the average product quality. By definition, incremental product quality refers to the quality of the dirtiest particle(s) present in the product, whereas the average product quality refers to the overall quality of a variety of differing quality particles present in the product. The plant optimization approach of equalizing incremental product qualities has limitations while dealing with multiple product quality constraints primarily due to the fact that the dirtiest particle with respect to the ash assay is rarely the same particle with respect to the sulfur assay. The maximum overall plant yield determined with respect to incremental ash is the result of a specific combination of individual circuit yields, which can be entirely different while maximizing the plant yield on the basis of incremental sulfur content. Thus, maintaining the required quality of the overall plant product with respect to both ash and sulfur will be difficult if one tries to maximize the plant yield on different basis.

The main objective of this research project was to develop a plant optimization model using an innovative genetic algorithms (GA) approach to maximize clean coal yield from a preparation plant while satisfying multiple product quality constraints. The continuous parameter GA approach was used for the optimization process for which a suitable objective function was developed by simultaneously considering the overall plant yield and the individual quality constraints. The initial yield values were generated randomly for the initial chromosome population between the lower and upper bound of yield values for the respective circuits obtained from the plant. The chromosomes were sorted on the basis of the value of the objective function. The best chromosomes were retained while the remaining chromosomes were discarded. The best chromosomes were then mated with each other to replenish the population, and the objective function was evaluated again. The crossover of the chromosomes takes place randomly to produce a new child. Some of the chromosomes were deliberately mutated to get out of local minima. The worst offspring soon died away. The chromosomes were then sorted based on increasing the value of the objective function so as to reach the global minimum and the whole process of reproduction, crossover and mutation was repeated until the convergence criteria were met. The whole process ended when the targeted constraints were achieved.

The unique features of GA include faster convergence, coverage of a wider search space, the ability to get out of local minima due to the mutation effect and the optimization of numerous variables at the same time. The overall approach pursued to complete this project is summarized as follows:

- Characteristic grade-recovery curves for each cleaning circuit of the Galatia Preparation Plant were developed through a detailed plant sampling program using a series of operating conditions.
• Characteristic incremental grade-recovery curves for each circuit were generated with respect to multiple product quality constraints, such as ash, sulfur and Btu contents (moisture content was reflected in the Btu calculations).
• Plant yield values were maximized using the incremental product quality approach on the basis of incremental ash, sulfur and Btu contents while satisfying plant product specifications of 7.5% ash, 1.2% sulfur and 13,600 Btu/lb. Similar exercises were conducted for several other hypothetical plant specifications, such as ash contents of 6.10%, 6.25%, 6.5%, 6.75%, 7.00 and 7.25%. A computer code was written to identify the global maxima for the plant from the maximum yield values generated using different incremental product qualities.
• The genetic algorithms (GA) approach was used to generate the maximum yield values for each product specification scenario for comparing the results with those obtained from the equalization of incremental product quality approach. The optimum plant yield values obtained from both approaches were very close to each other and more than 1.2% higher than the plant yield currently achieved while treating at least two different coal blends (75:25 and 60:40) obtained from the Galatia North and Millenium portals of the Galatia underground mine.

Galatia Mine’s coal preparation plant currently treats nearly 2,100 tph of run-of-mine (ROM) coal and achieves maximum plant yields of 52.1% and 58.0% while cleaning the aforementioned blends of coal and satisfying the aforementioned product quality constraints. Separation specific gravity of 1.40 is maintained in heavy media vessels and heavy media cyclones, which treat more than 80% of the ROM coal. However, the plant optimization models developed as a part of this project indicate that higher specific gravity of separation has to be maintained in both heavy media vessel and heavy media cyclone circuits to improve the overall plant yield by at least 1.2%, or an additional 20 tph of clean coal. The recommended specific gravities of separation for the heavy media vessels and heavy media cyclones are 1.72 and 1.54, respectively.
OBJECTIVES

To accomplish the goal of using genetic algorithms (GA) in developing a comprehensive model for optimization of the total plant system, the specific research objectives were:

- To generate the characteristic grade-recovery curve for each cleaning circuit of an operating plant by undertaking a detailed plant sampling program.
- To generate independent series of maximized plant yield values on the basis of equalized incremental ash, sulfur and Btu contents over a range of product qualities.
- To determine the best plant yield value that can be attained while simultaneously satisfying a given set of product constraints by utilizing the GA-based optimization procedure.
- To compare results obtained from the GA-based model and the model based on incremental product quality to the existing plant performance and quantify the improvement in clean coal production achievable from a given plant.

INTRODUCTION AND BACKGROUND

A majority of raw coal produced at mines in eastern and midwestern states is cleaned in coal preparation plants to improve product quality. The run-of-mine (ROM) coal entering a coal preparation plant is typically cleaned using three or four individual circuits based on the size consist of the coal. For example, coals coarser than ½-inch may be cleaned in a heavy medium vessel circuit, ½-inch x 1-mm in a heavy medium cyclone circuit, 1-mm x 150-micron in a spiral circuit and minus 150 micron size coal in a flotation circuit. The moisture content of the clean coal increases as the particle size being cleaned decreases. However, the ash and sulfur contents of the products from each circuit are maintained at nearly the same level as the required clean coal product specification for the overall plant. In other words, if a plant contract requires product specifications of 8% ash and 1.2% sulfur, the operating conditions in the individual circuits are so maintained that the ash and sulfur contents of the individual products are nearly 8% and 1.2%, respectively. Although this approach of producing equal average product quality from each circuit provides a simplistic solution to satisfy contract specifications, it does not necessarily guarantee the maximum possible plant yield.

Numerous studies (Salama, 1986, 1991; Lyman, 1992; Rong, 1992; Sen et al., 1994; Honaker et al., 1997) have been conducted in the past to develop suitable procedures for maximizing overall plant yield while satisfying a desired product quality. Some of these studies recommended a graphical approach, whereas others recommended an analytical approach. However, the essential step was the same with both approaches. Equalization of incremental product quality obtained from the individual circuits operating in a plant was recommended as the necessary step to achieve maximum possible yield while satisfying a given product quality constraint.

Incremental product quality refers to the quality of the dirtiest particle(s) present in the
clean coal product, whereas the average product quality refers to the overall quality of a variety of differing quality particles present in the clean coal product. However, this technique alone can help maximize the clean coal yield only when there is just one quality constraint for the product. If multiple quality constraints can somehow be combined to form one constraint, the equalization of incremental product quality approach alone may still be used to maximize the clean coal yield from a plant. For example, ash and sulfur contents can be combined to form a new constraint, such as lb. of SO₂/MBtu. The numerator of this new constraint is a function of the sulfur content, whereas the denominator is directly correlated to the ash content. Thus, based on the desired ash and sulfur content in the product, the target SO₂/MBtu may be calculated and then the iterative optimization process can be initiated by equalizing the incremental SO₂/MBtu in individual cleaning circuits until the target SO₂/MBtu content of the overall plant product is reached.

However, this approach has limited application due to the fact that it may not always be possible to generate a single quality constraint by combining a variety of required product constraints that may include moisture content. Thus, it was decided to investigate the use of the powerful GA optimization tool that has the ability to include numerous quality constraints in the optimization process.

Genetic Algorithms (GA):

GA is an innovative tool that has been successfully used in solving many complex optimization problems. GA operates on grouped pieces of information called chromosomes (Haupt and Haupt, 1999; Goldberg, 1989). The chromosomes contain all the information about the potential candidates for a minimization/maximization problem in the form of an array of parameters called genes. An objective function is evaluated for all the existing chromosomes in each iteration. The best chromosomes are kept and the worst discarded. The best chromosomes are then mated with each other to replenish the population, and the objective function evaluated again. Mating is defined as the creation of a new population (using the existing candidates) of possible candidates to replenish the pool that was discarded. Mating is done through a process called crossover, a heuristic or numerical process that uses two candidates from the existing pool to create two new candidates called offsprings. Some of the chromosomes are deliberately mutated to help in getting the search out of local extrema. Mutation is defined as deliberately changing some parameters in some candidates.

This GA process is illustrated in Figure 1. The unique features of GA include much faster convergence, coverage of a much wider search space, the ability to get out of local extrema due to the mutation effect, and the optimization of numerous variables at the same time. A typical solution series obtained using the GA is illustrated in Figure 2.
Define Parameters and Cost Function

Create Population

Evaluate Cost
  Select Mate
  Reproduce
  Mutate

Test convergence

Figure 1: A flow chart showing the step-wise approach followed in genetic algorithms

Figure 2: Convergence of genetic algorithms to a solution after 40 generations
EXPERIMENTAL PROCEDURES

A simplified flowsheet of Galatia Mine’s coal preparation plant is shown in Figure.3. The plant receives feed from two vastly different sections of the underground mine (Galatia North and Millennium). The ROM coal is blended in a desired ratio depending on the availability of coal from the two sections before being fed to the plant. The plant uses heavy media systems to clean all of the coal coarser than 1-mm. The plant feed is screened to separate the coarser coal into two size fractions, 152-mm x 16-mm (6-inch x 5/8-inch) and 16-mm x 1-mm (5/8-inch x 16-mesh) to be treated by heavy media vessels and heavy media cyclones, respectively. The coal particles finer than 1 mm (16 mesh) are classified by banks of 15-inch diameter classifying cyclones into plus 150-µm (100-mesh) and minus 150-µm (100-mesh) fractions. The coarser fraction (1000-µm x 150-µm) is treated in spiral circuits, whereas the finer particles (minus 150-µm) are further classified into two fractions, 150-µm x 45-µm (100-mesh x 325-mesh) and minus 45-µm (325-mesh) using two banks of 6-inch diameter classifying cyclones. The minus 45-µm size fraction is discarded as slimes while the 150-µm x 45-µm (100-mesh x 325-mesh) material serves as the feed for the flotation circuit. The feed rate to the entire plant is around 2,100 stph, of

Figure 3: A simplified flow-sheet for Galatia Mine’s coal preparation plant incorporating four parallel cleaning circuits
which approximately 40% is cleaned by heavy medium vessels, 43% by heavy media cyclones, 12% by spirals and the remaining 5% by conventional flotation cells.

This project exercise started with a detailed sampling program to generate the grade-recovery curves from each cleaning unit operating in the plant. The raw coal samples corresponding to 100% Galatia North and 100% Millennium sections were collected to separately study their size distribution and washability characteristics to enable the determination of the feed characteristics for any specific blend of coal. During the detailed plant testing, the plant was receiving a blend of 75:25 (Galatia North: Millennium). A series of plant tests were conducted on different operating days with samples collected as shown in Figure 4. Individual sets of feed, product and tailing samples were collected for each plant experiment conducted with the coarse coal circuits (heavy media vessel and heavy media cyclone) at five different medium specific gravities, 1.32, 1.36, 1.40, 1.44 and 1.48. Although intended, higher medium densities could not be tested due to practical operating constraints in the plant. Based on the collected data, suitable partition models were developed using a modified Lynch equation described as follows:

\[ PN_{\text{float}} = \frac{e^{ax} - 1}{e^{ax} + e^a - 2} \]

where  
- \( PN \) = partition coefficient  
- \( x \) = reduced specific gravity \( \left( \frac{D_m}{D_{50}} \right) \)  
- \( D_m \) = mean density; \( D_{50} \) = separation density  
- \( a \) = fitting constant represented by the slope of the partition curve

These partition models were utilized to predict the separation performance from both heavy media cyclone and heavy media vessel when operated at higher medium specific gravities than actually tested.

For spirals and flotation cells, splitter position and froth heights were considered as the critical operating conditions, respectively. Independent samples were collected from feed, product and tailings streams of spirals at five different splitter positions varying from \( \frac{1}{2} \)-inch to \( 2\frac{1}{2} \)-inch. Similar samples were collected from the flotation circuit by setting the froth heights in the flotation cells at five different levels ranging from 3 inches to 11 inches. All test samples were analyzed for ash and sulfur and selected samples underwent full washability analysis as well. The washability data were used to generate the partition coefficient which was in turn used to develop the characteristic grade-recovery curves for heavy media vessels, heavy media cyclones and spirals. Flotation kinetic studies were conducted on flotation feed samples to develop an appropriate model for representing the entire grade-recovery curve achievable from the flotation cells. All these data were utilized for the optimization process to determine overall maximum yield at desired product quality constraints using both the incremental product quality approach and the GA approach.

Additional plant tests were conducted to validate some of the model predictions while using a different blend of coal (60:40) from the Galatia North and Millennium sections.
RESULTS AND DISCUSSIONS

The activities of this plant optimization project were subdivided into four research tasks. The results obtained from these individual tasks are discussed in the following sections;

Task 1: A Detailed Plant Test Program

The plant optimization models developed during this project require a series of input data describing the performance of the individual cleaning circuits operating in the plant. The input data include characteristic grade-recovery curves for each circuit. The grade-recovery relationships generated from the actual plant test data are shown in Figures 5 (a) and (b) for heavy media vessels and heavy media cyclones, and in Figures 6 (a) and (b) for plant spirals and flotation banks. As shown in Figure 5 (a), the total mass yield from heavy media vessels varied from 53.2% to 64.3% with a relatively small change in ash contents from around 6.05% to 6.95% when the medium specific gravity was raised from 1.32 to 1.48 in four steps. For a similar change in medium density, the mass yield obtained from heavy media cyclones increased from nearly 31.9% to 43.4% with a corresponding increase in product ash content from 5.85% to 7.10%. The relatively low mass yield values for heavy media cyclones was a result of much higher ash content in the feed coal (50.2% compared to 37.1% feed ash content at the heavy media vessels). Although it was intended to raise the medium density for both heavy media circuits to higher levels, it was not achievable due to operating constraints in the plant.

The grade-recovery curve for the coal spirals, shown in Figure 6 (a), was generated by varying the splitter-position in one of the spiral banks from 0.5-inch to around 2.5-inch from the outside of the spiral profile. With a feed ash content of 33.4%, the resulting
Figure 5: Grade-recovery curves for (a) heavy media vessels and (b) heavy media cyclones operating at Galatia Mine’s preparation plant
Figure 6: Grade-recovery curves for (a) spirals and (b) flotation cells operating at Galatia Mine’s preparation plant.
change in mass yield and product ash content were from 55.1% to 64.8% and 5.08% to 5.56%, respectively. For flotation cells, froth height was varied over a range of 11 inches to 3 inches to raise mass yield values from 19.7% to 26.6% with a corresponding increase in product ash content from 9.65% to 11.6%, as shown in Figure 6 (b). A high feed ash content of nearly 50% in the flotation feed may partly explain the extremely low mass yield values. However, it was found that a significant amount of minus 45-micron fine coal slurry was also being fed to the flotation cells, which were supposed to be cleaning only the 150 x 45 micron size coal. The presence of excess fine particles may have also partly caused the unexpected low mass yield values obtained from the flotation cells.

Task 2: Plant Sample Analysis

All collected plant samples (more than two hundred samples including the washability density fractions) were subjected to ash and sulfur analysis, the later being done at the laboratory facility of the Galatia plant. Washability analyses (float-sink tests) were conducted on a total of 30 bulk samples obtained from the three density-based cleaning circuits whereas two flotation feed samples were subjected to kinetic and release analyses. Organic density solutions in bulk quantity were used at the large scale washability facility of the Galatia plant for analyzing the coarser samples. On the other hand, the washability analyses of the finer samples were conducted at the Illinois Coal Development Park. The details of the individual washability analysis are provided in the Appendix section of this report.

Five sets of partition curves were generated using the float-sink data for each test conducted with heavy media vessel, heavy media cyclone and spiral circuit. Mean probable error (Ep) and the corresponding density cut points (D50) were determined using these partition curves and summarized in Table 1. The partition curves for each cleaning circuit were then normalized by plotting the partition coefficients as a function of D/D50. The normalized partition curves for heavy media vessel, heavy media cyclone and spiral circuits are shown in Figures 7 (a-c), respectively. Various model equations were investigated to fit the normalized partition data for each circuit and finally a modified Lynch equation was found as the best fit equation for both heavy media circuits.

<table>
<thead>
<tr>
<th></th>
<th>Heavy Media Vessel</th>
<th>Heavy Media Cyclone</th>
<th>Spiral</th>
</tr>
</thead>
<tbody>
<tr>
<td>D50</td>
<td>Ep</td>
<td>D50</td>
<td>Ep</td>
</tr>
<tr>
<td>1.413</td>
<td>0.0965</td>
<td>1.35</td>
<td>0.0565</td>
</tr>
<tr>
<td>1.483</td>
<td>0.09</td>
<td>1.387</td>
<td>0.0415</td>
</tr>
<tr>
<td>1.507</td>
<td>0.0765</td>
<td>1.41</td>
<td>0.05</td>
</tr>
<tr>
<td>1.487</td>
<td>0.08</td>
<td>1.46</td>
<td>0.0535</td>
</tr>
<tr>
<td>1.51</td>
<td>0.06</td>
<td>1.42</td>
<td>0.053</td>
</tr>
</tbody>
</table>

(a)
Figure 7: Normalized partition data along with the modified Lynch model for (a) heavy media vessels (b) heavy media cyclones and (c) spirals
These model equations were utilized to predict the partition coefficients and the mass yields corresponding to the entire range of specific gravity values from 1.15 to 2.35, as shown in Figure 8 (a). Since plant flotation experiments failed to provide meaningful data, flotation performance was predicted using the flotation kinetic analysis conducted on the flotation feed sample, the results of which are plotted in Figure 8 (b). A release analysis was also conducted to investigate the best flotation performance achievable. The flotation kinetics plot used for flotation rate constant calculation and the release analysis curve are shown in Figures A.1 and A.2 in the Appendix.

(a)

![Graph showing grade-recovery curves for different cleaning circuits.](image)

(b)

![Graph showing yield over time for flotation circuits.](image)

Figure 8. Grade-recovery curves generated for (a) density-based cleaning circuits and (b) flotation circuits based on best fit empirical model equations.
**Task 3: Development of a Plant Optimization Model**

**Task 3.1: Equalization of Incremental Product Quality:**

Based on the sample analyses results obtained from Task 2, the characteristic grade-recovery curves for each cleaning circuit were generated separately on the basis of ash, sulfur and Btu assays as shown in Figures A.3-A.5 in the Appendix. Using the yield-grade data, yield-incremental grade relationship was developed for each circuit as shown in Figures A.6-A.8 on the basis of incremental ash, sulfur and Btu contents, respectively.

Then, following the equalization of incremental grade approach, the overall plant yield was maximized for a range of plant product grades. This approach was followed using each type of product assays, such as ash, sulfur and Btu and thus, 3 different series of maximized clean coal yield values were generated. Using a computer program, the global maximum plant yield was determined while satisfying a variety of target grades as listed in Table 2. The corresponding key operating conditions that would produce the maximum yield are also listed in Table 2. As indicated, the maximum mass-yield values achievable from the plant varies from 50.91% to 56.11% with an increase in plant product ash content from 6.10% to 7.5%, while maintaining the product sulfur constraint constant at 1.3%.

One interesting finding related to the anomalies observed when maximum yield is calculated on the basis of different product quality constraints is illustrated in Figures 9 (a-c). The three plots show the maximum yield values achievable as a function of product ash, sulfur and Btu contents, respectively, by the equalization of three incremental product qualities, such as incremental product ash, incremental product sulfur and incremental product Btu content. Clearly, the three curves are different from each other. Since even ½% difference in the overall plant yield is of enormous monetary value, such differences, although small, should not be overlooked. It will be increasingly difficult to determine the global maximum plant yield value with an increasing number of product quality constraints. Therefore, an alternative method of plant optimization was developed in the project Task 3.2.

A careful examination of these plots reveal that the maximum yield versus product quality relationship developed is the best when it is obtained by equalizing the same specific incremental product quality. For example, the maximum plant yield versus product ash content curve is the best when obtained by equalizing incremental product ash contents in all cleaning circuits. Similarly, the maximum plant yield versus product sulfur content curve is the best when obtained by equalizing incremental product sulfur contents in all cleaning circuits. The plant optimization model developed using the incremental product quality approach consists of a computer code using Microsoft Access and MatLab with a Visual Basic front end, which makes the model user-friendly. All input parameters, such as feed washability and size-by-size data, may be directly entered on a screen similar as shown in Figure 10.
Table 2: The maximized plant yield values obtained for a series of hypothetical target quality constraints for the Galatia plant with 75% ROM coal from the Galatia North section and 25% from the Millennium section of the mine.

<table>
<thead>
<tr>
<th>Plant Constraint</th>
<th>Operating Conditions</th>
<th>HMV</th>
<th>HMC</th>
<th>Spiral</th>
<th>Flotation</th>
<th>Overall</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ash = 6.1%</td>
<td>D50</td>
<td>1.56</td>
<td>1.37</td>
<td>1.50</td>
<td>Splinter Position A = 6.5&quot;, B = 1&quot;</td>
<td>Residence Time 64 seconds</td>
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<tr>
<td>Sulfur = 1.3 %</td>
<td>Yield (%)</td>
<td>61.34</td>
<td>38.09</td>
<td>62.84</td>
<td>41.27</td>
<td>50.91</td>
</tr>
<tr>
<td></td>
<td>Ash (%)</td>
<td>6.70</td>
<td>6.11</td>
<td>4.07</td>
<td>9.04</td>
<td>6.10</td>
</tr>
<tr>
<td></td>
<td>Sulfur (%)</td>
<td>1.042</td>
<td>1.189</td>
<td>0.999</td>
<td>0.900</td>
<td>1.038</td>
</tr>
<tr>
<td></td>
<td>Btu (as received)</td>
<td>13596</td>
<td>13685</td>
<td>14060</td>
<td>13602</td>
<td>13707</td>
</tr>
<tr>
<td>Ash = 6.25%</td>
<td>D50</td>
<td>1.59</td>
<td>1.41</td>
<td>1.53</td>
<td>Splinter Position A = 6.5&quot;, B = 1.2&quot;</td>
<td>Residence Time 70 seconds</td>
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<td>Yield (%)</td>
<td>64.21</td>
<td>39.60</td>
<td>64.44</td>
<td>42.92</td>
<td>52.18</td>
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<tr>
<td></td>
<td>Ash (%)</td>
<td>6.78</td>
<td>6.33</td>
<td>4.26</td>
<td>9.17</td>
<td>6.25</td>
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<td>Sulfur (%)</td>
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<td>1.222</td>
<td>1.009</td>
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<tr>
<td></td>
<td>Btu (as received)</td>
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<td>13652</td>
<td>14033</td>
<td>13588</td>
<td>13666</td>
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<tr>
<td>Ash = 6.5%</td>
<td>D50</td>
<td>1.65</td>
<td>1.50</td>
<td>1.60</td>
<td>Splinter Position A = 6.5&quot;, B = 1.4&quot;</td>
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<td>Yield (%)</td>
<td>66.34</td>
<td>41.28</td>
<td>66.54</td>
<td>45.74</td>
<td>53.74</td>
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<tr>
<td></td>
<td>Ash (%)</td>
<td>6.92</td>
<td>6.68</td>
<td>4.60</td>
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<td></td>
<td>Sulfur (%)</td>
<td>1.065</td>
<td>1.276</td>
<td>1.030</td>
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<td></td>
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<td>13599</td>
<td>13988</td>
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<td>Yield (%)</td>
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<td>Ash (%)</td>
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<td>4.72</td>
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<td>1.66</td>
<td>1.67</td>
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<td>Yield (%)</td>
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<td>67.53</td>
<td>50.39</td>
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<td>4.88</td>
<td>11.05</td>
<td>7.00</td>
</tr>
<tr>
<td></td>
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<td>1.71</td>
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<td>43.39</td>
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<td>52.84</td>
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<td>68.20</td>
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<td>7.85</td>
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<td>5.29</td>
<td>7.49</td>
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<td>Sulfur (%)</td>
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<td>1.362</td>
<td>1.112</td>
<td>1.112</td>
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<td>Btu (as received)</td>
<td>13448</td>
<td>13422</td>
<td>13894</td>
<td>13894</td>
<td>13124</td>
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</table>
Figure 9. Maximum plant yield versus product quality relationship with respect to (a) product ash content, (b) product sulfur content and (c) product Btu content.
Figure 10: An example of the front end of the plant optimization model developed in this project
Task 3.2: Optimization using Genetic Algorithms (GA):

The GA technique was used to determine the optimal plant yield while satisfying multiple product quality constraints, i.e. product ash, sulfur and Btu content. Chromosomes were developed that encode the main parameters (yield values) in individual cleaning circuits. The initial yield values were generated randomly for the initial population of the chromosomes between the lower and upper bound of yield values for the respective circuits obtained from the plant. Thus, each yield value had a corresponding density set point for density-based separation circuits and residence time for flotation circuit and associated ash, sulfur, and Btu content. This initial universe of chromosomes was termed Nipop.

\[
\text{Chromosome} = [Y_1 \ Y_2 \ Y_3 \ Y_4]
\]

where, \(Y_1\), \(Y_2\), \(Y_3\) and \(Y_4\) are the respective yield values (genes) for heavy medium vessel, heavy medium cyclone, spiral and flotation circuits in the plant. An objective function was evaluated for all the existing chromosomes in each iteration. The objective function (or cost function) is defined as

\[
\text{Objective Function} = f(Y, \Delta A, \Delta S, \Delta B) = w_Y Y + w_A \Delta A + w_S \Delta S + w_B \Delta B
\]

where

- \(Y\) = overall yield of the plant
- \(\Delta A\) = difference of targeted plant product ash and the actual plant product ash
- \(\Delta S\) = difference of targeted plant product sulfur and the actual plant product sulfur
- \(\Delta B\) = difference of targeted plant product Btu and the actual plant product Btu
- \(w_Y, w_A, w_S, w_B\) are the weights.

The chromosomes were sorted on the basis of the minimum value of the objective function (i.e. the negative of the plant yield values). The negative sign is added due to the fact that the GA technique is traditionally used to solve minimization problems. The best chromosomes (i.e. those with least negative plant yield value) are the first chromosome followed by ones that are of decreasing cost. The lower portion (usually bottom 50%) of this population was eliminated to form a new population containing only half of the best chromosomes of the previous iteration. This new population is called Npop, and is termed as the working population. Next, couples were selected from this population and offsprings produced by crossover techniques. The crossover of the chromosomes takes place randomly to produce new children as shown in Figure 11. The last two genes of Parent 1 and Parent 2 were replaced by each other to give Child 1 and Child 2. In Figure 11, \(Y_{11} \ & \ Y_{12}, \ Y_{21} \ & \ Y_{22}, \ Y_{31} \ & \ Y_{32}\) and \(Y_{41} \ & \ Y_{42}\) represent the yield values of heavy media vessel, heavy media cyclone, spiral and flotation circuits. It was hoped that
two good parents would lead to better offsprings and if it did, this offspring would climb up to the top of the list. If the offspring was not as good as the parents, it would eventually be eliminated. The fitness value of the new offspring thus produced was evaluated and the lower half population of the parent generation was replaced by the new offspring based on the minimum value of the objective function.

Some of the chromosomes were deliberately mutated to get out of local minima. Since mutation allows the solution to be kicked out of local minima, there is a high probability of converging to the global minima. Mutation was accomplished by selecting a few of the remaining good chromosomes and deliberately changing a few yield values in a completely random fashion. The worst offspring was soon eliminated. The whole process stopped after the plant product qualities matched the targeted plant product qualities and the top chromosome had been identified as the solution to the optimization process.

The same set of data was used for the GA-based plant yield optimization as was used for the equal incremental approach. The initial grade-recovery data as generated by the predicted equation for each circuit were used to generate the yield values randomly for GA analysis within realistic limits. The results were obtained for the same plant constraints as produced by the incremental approach and summarized in Table 3. As indicated, the maximum mass-yield values achievable from the plant varies from 50.78% to 56.11% with an increase in plant product ash content from 6.10% to 7.5%, while maintaining the product sulfur constraint constant at 1.3%. The results thus obtained by the GA-based analysis are very close to that obtained by the incremental approach, which are the theoretical best achievable yield values. However, with the GA approach, the analysis is done by simultaneously considering all the product quality constraints and thus, one global maximum yield value is achieved after the optimization steps are complete unlike the incremental product quality approach, which adds to the complexities of the later process.

![Crossover of the chromosomes at selected point (shown by dashed line) chosen randomly](image)
<table>
<thead>
<tr>
<th>Plant Constraint</th>
<th>Operating Conditions</th>
<th>HMV</th>
<th>HMC</th>
<th>Spiral</th>
<th>Flotation</th>
<th>Overall</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ash = 6.1%</td>
<td>D50</td>
<td>1.56</td>
<td>1.37</td>
<td>1.50</td>
<td>A = 6.5&quot;, B = 1&quot;</td>
<td>65 seconds</td>
</tr>
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<td>Yield (%)</td>
<td>61.40</td>
<td>37.68</td>
<td>62.99</td>
<td>42.00</td>
<td>50.78</td>
</tr>
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<td>6.71</td>
<td>6.06</td>
<td>4.08</td>
<td>9.06</td>
<td>6.99</td>
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<td>1.000</td>
<td>0.900</td>
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<td>47.57</td>
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<td>67.30</td>
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<td>56.11</td>
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As shown in Table 4, actual plant performance is compared with the optimized plant performance predicted using both approaches. The overall plant yield achieved with a 75:25 blend of coal is 52%, whereas the optimized results predicted are more than 2.5% higher while satisfying similar product quality constraints. As indicated, the relatively low yield achieved from the plant is mainly due to the low medium density of 1.40 maintained for the heavy media cyclone circuit, which cleans nearly 43% of the ROM coal in contrast to the recommended 1.54 level. Possible improvements from the spiral circuit, which cleans only 12% of the ROM coal, are also quite significant.

Table 4. A comparative analysis of the actual plant data with the plant optimization data generated using GA and incremental product quality approaches for a 75:25 blend of coal.
Task 4: Additional Plant Testing:

The actual validation of the plant optimization model was not feasible since the plant’s operating environment did not allow raising the medium densities beyond 1.50 specific gravity in the dense media cleaning circuits. However, additional plant tests were conducted using another blend (60:40) of coal to verify the empirical model equations developed for various cleaning circuits. As indicated in Table 5, the total plant yield achieved for this blend of coal was 58.03% whereas the maximum yield predicted using GA approach was 59.16%.

Table 5. A comparative analysis of the actual plant data with the plant optimization data generated for another blend (60:40) of coal treated by the Galatia plant

<table>
<thead>
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<th>Actual Plant Data</th>
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<th>HMC</th>
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<th>Flotation</th>
<th>Overall</th>
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<td>9639</td>
<td>7345</td>
<td>7926</td>
<td><strong>8186</strong></td>
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<tr>
<td><strong>Product Characteristics</strong></td>
<td>Operating Conditions</td>
<td>D50</td>
<td>D50</td>
<td>D50</td>
<td>Splitter Position</td>
<td>Residence Time</td>
</tr>
<tr>
<td></td>
<td>Yield (%)</td>
<td>48.50</td>
<td>69.54</td>
<td>49.67</td>
<td>57.58</td>
<td><strong>58.03</strong></td>
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<tr>
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<td>Ash (%)</td>
<td>6.48</td>
<td>6.26</td>
<td>5.75</td>
<td>10.35</td>
<td><strong>6.39</strong></td>
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<td>Sulfur (%)</td>
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<th>HMC</th>
<th>Spiral</th>
<th>Flotation</th>
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<td>Operating Conditions</td>
<td>D50</td>
<td>D50</td>
<td>D50</td>
<td>Splitter Position</td>
<td>Residence Time</td>
</tr>
<tr>
<td></td>
<td>Yield (%)</td>
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<td>62.17</td>
<td>77.63</td>
<td>56.73</td>
<td><strong>59.25</strong></td>
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<td>6.16</td>
<td>5.02</td>
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<td>Sulfur (%)</td>
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<td>49.44</td>
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<td>77.60</td>
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<tr>
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<td>Ash (%)</td>
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<td>6.15</td>
<td>5.01</td>
<td>7.76</td>
<td><strong>6.36</strong></td>
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<td>1.059</td>
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CONCLUSIONS AND RECOMMENDATIONS

A plant optimization study investigated the use of genetic algorithms (GA), an innovative optimization technique, for the first time in a coal preparation plant application. The study was successfully completed utilizing American Coal Company’s Galatia Mine preparation plant as the host site.

Conclusions:

- The modified Lynch equation was found to fit well to the plant performance data generated from the heavy media circuits. Flotation performance was better modeled using the flotation kinetics data.
- The incremental product quality approach of plant optimization produced nearly 2.6% and 1.2% increase over the existing plant yield value of 52.1% and 58.0% for two different blends of coal, respectively, while satisfying nearly the same product quality constraints. The GA approach produced similar plant yield improvements of 2.5% and 1.2%, respectively for the two coal blends.
- The limitations of the incremental product quality approach while dealing with multiple product quality constraints were further explained by the anomalies in the maximum plant yield versus product quality relationship generated with respect to three individual product quality constraints, i.e. product ash, sulfur and Btu content. Thus, the GA approach is the recommended approach for plant optimization.

Recommendations:

It must be realized that there may be a difference in the predicted maximum and actual maximum plant yield values due to constant fluctuation in feed characteristics of a plant. Such a problem can be resolved by continuously monitoring the plant feed characteristics through on-line washability analyzers, which are emerging fast in the processing world. The actual benefits of plant optimization can be realized through the installation of on-line washability analyzers in operating plants and integrating them with plant PLCs. This will allow the automatic adjustment of medium densities with any significant change in the feed characteristics to help maximize the overall plant yield.

ACKNOWLEDGEMENTS

The Principal Investigators greatly appreciate the dedicated effort of the plant optimization research team, which includes Dr. S.K. Biswal and Mr. Vishal Gupta for the successful completion of this research project. Special thanks go to Mr. Bob Milligan, Mr. John Hargis of the Galatia Mine Preparation Plant for their special assistance during this project. The research funds from the ICCI/DCEO and the cooperation of the Coal Research Center at SIU are sincerely appreciated. Without their support, this project would not have been feasible.
DISCLAIMER STATEMENT

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REFERENCES


APPENDIX
Figure A. 1: Kinetic analysis of flotation samples

Figure A. 2: Release analysis of flotation samples
Figure A. 3. Predicted ash-yield curves

Figure A. 4. Predicted sulfur-yield curves
Figure A. 5: Predicted Btu-recovery curves

Figure A.6: Predicted yield curves with incremental sulfur
Figure A.7: Predicted yield curves with incremental ash

Figure A.8: Predicted yield curves with incremental Btu
## Washability Results of Heavy Media Vessel

### Test 1

<table>
<thead>
<tr>
<th>Density (R.D.)</th>
<th>Mean</th>
<th>Dm/D50</th>
<th>Feed</th>
<th>Reject</th>
<th>% of feed</th>
<th>PN(float)</th>
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<td>wt(%)</td>
<td>Reject wt(%)</td>
<td>float wt(%)</td>
<td>(%)</td>
<td>(%)</td>
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<th>PN(float)</th>
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<th>% of feed Reject (%)</th>
<th>float wt(%)</th>
<th>PN(float) (%)</th>
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# Washability Results of Heavy Media Cyclone

## Test 1

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<th>Relative Density (R.D.)</th>
<th>Mean R.D. (Dm)</th>
<th>Dm/D50</th>
<th>Float wt(%)</th>
<th>Reject wt(%)</th>
<th>% of feed Reject (%)</th>
<th>Calculated Float (%)</th>
<th>PN(float)</th>
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<th>Reject wt(%)</th>
<th>% of feed Reject (%)</th>
<th>Calculated Float (%)</th>
<th>PN(float)</th>
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<th>Reject wt(%)</th>
<th>% of feed Reject (%)</th>
<th>Calculated Float (%)</th>
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<th>% of feed</th>
<th>Calculated</th>
<th>PN(float)</th>
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<td>1.16</td>
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<td>10.62</td>
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<td>1.5625</td>
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<td>3.41</td>
</tr>
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<td>1.24</td>
<td>0.28</td>
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<td>0.11</td>
<td>2.77</td>
<td>2.88</td>
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<tr>
<td>2.0-2.8</td>
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Test 5

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<th>Dm/D50</th>
<th>Float</th>
<th>Reject</th>
<th>% of feed</th>
<th>Calculated</th>
<th>PN(float)</th>
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<tbody>
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<td>1.275</td>
<td>0.90</td>
<td>25.28</td>
<td>1.17</td>
<td>10.87</td>
<td>0.66</td>
<td>11.53</td>
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<tr>
<td>1.3-1.4</td>
<td>1.35</td>
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<td>12.41</td>
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<td>5.33</td>
<td>0.88</td>
<td>6.22</td>
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<tr>
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<td>1.68</td>
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<td>0.11</td>
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<td>100</td>
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<td>57.02</td>
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### Washability Results of Spiral

#### Test 1

<table>
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<tr>
<th>Relative Density (R.D.)</th>
<th>R.D. (Dm)</th>
<th>Dm/D50</th>
<th>Float wt(%)</th>
<th>% of feed float (%)</th>
<th>Calculated feed (%)</th>
<th>PN(float) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.15-1.3</td>
<td>1.225</td>
<td>0.83</td>
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<td>99.23</td>
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<td>0.72</td>
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<td>31.64</td>
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#### Test 2

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<th>R.D. (Dm)</th>
<th>Dm/D50</th>
<th>Float wt(%)</th>
<th>% of feed float (%)</th>
<th>Calculated feed (%)</th>
<th>PN(float) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.15-1.3</td>
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<td>0.94</td>
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<td>11.61</td>
<td>17.30</td>
<td>67.09</td>
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<td>1.01</td>
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<td>2.39</td>
<td>5.34</td>
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<td>1.38</td>
<td>0.76</td>
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<td>30.43</td>
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<td>1.02</td>
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#### Test 3

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<th>R.D. (Dm)</th>
<th>Dm/D50</th>
<th>Float wt(%)</th>
<th>% of feed float (%)</th>
<th>Calculated feed (%)</th>
<th>PN(float) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.15-1.3</td>
<td>1.225</td>
<td>0.81</td>
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<td>93.65</td>
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<td>1.5625</td>
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<td>0.78</td>
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<td>1.8125</td>
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### Test 4

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<th>Dm/D50</th>
<th>Float</th>
<th>% of Feed</th>
<th>Calculated</th>
<th>PN(float)</th>
</tr>
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<td>71.96</td>
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### Test 5

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<th>Mean R.D. (Dm)</th>
<th>Dm/D50</th>
<th>Float</th>
<th>% of Feed</th>
<th>Calculated</th>
<th>PN(float)</th>
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<td>1.15-1.3</td>
<td>1.225</td>
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### Kinetic Results of Flotation samples

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<th>Sample</th>
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<th>Weight (%)</th>
<th>Ash (%)</th>
<th>Sulfur (%)</th>
<th>Cu. wt. Ash (%)</th>
<th>Cu. wt. Sulfur (%)</th>
<th>ln((R/\infty/(R/\infty - R)))</th>
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