An Evaluation of Plantwide Control Strategies for Coal Preparation Plants

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The quality of cleaned products from coal preparation plants is often variable due to natural fluctuations in the washability characteristics of the plant feed. To combat this problem, many modern plants have installed on-line analyzers that provide feedback for the real-time control of product quality via the adjustment of circuit cutpoints. Unfortunately, optimization studies show that this approach may actually lead to increased losses of saleable coal. This paper discusses the problems associated with the real-time manipulation of circuit cutpoints and suggests alternative modes of operation that are better suited for plant optimization. A case study involving an eastern U.S. coal plant has been used to compare the economic impacts of these different approaches for plantwide control.

INTRODUCTION

Coal preparation is routinely used to produce carbon-rich products for the utility (steam) and metallurgical (coke) coal markets. In the U.S. alone, there are currently 267 coal preparation plants operating in 16 states. These plants generate approximately 393 million tons of clean coal annually, which represents about 36% of the total U.S. coal production. Because of the large volumes of material treated, a tremendous financial incentive exists for coal producers to improve the efficiency of their processing operations. Data from a recent field study suggest that a one-percentage point improvement in plant efficiency can be equivalent to a 15–20% improvement in mine profitability.

This article provides a review of the basic concepts of yield optimization as applied to parallel processing circuits such as those employed by modern coal preparation plants.

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These concepts have been used (i) to identify the problems associated with the real-time manipulation of circuit cutpoints and (ii) to suggest alternative modes of operation that are better suited for plantwide control. The economic impacts of these different approaches to plant optimization have been compared by means of a case study involving an eastern U.S. coal plant.

PLANT OPTIMIZATION

Problem Statement

Coal preparation plants incorporate several parallel circuits partitioned according to particle size. The clean coal yield (*Y*) and quality (*Q*) for a plant consisting of n parallel circuits can be calculated from simple weighted averages using:

$$Y = \sum_{i=1}^{n} S_i Y_i \qquad \text{(EQ 1)}$$

$$Q = \sum_{i=1}^{n} S_i Y_i Q_i / \sum_{i=1}^{n} S_i Y_i \qquad \text{(EQ 2)}$$

in which S_i is the percentage of feed coal reporting to circuit *i*, Y_i is the clean coal yield from the separator in circuit *i*, and Q_i is the coal quality produced by the separator in circuit *i*. The plant yield is normally limited by one or more constraints imposed on product quality. Consequently, most plant operators select circuit cutpoints to ensure that the quality constraints are not exceeded in any given circuit, i.e., all circuits are set to produce the same quality. This objective is often difficult to achieve in practice due to natural fluctuations in the feed coal characteristics. To help alleviate this problem, a number of plants have installed on-line analyzers to provide instantaneous feedback regarding overall product quality. The control loops are generally configured to mimic the traditional operating philosophy of maintaining constant quality in all circuits. Circuit adjustments may be either manual (input by the operator) or automatic, depending on the level of control desired. Although this approach generally improves the consistency of the overall clean coal product, it does not ensure that the maximum plant yield has been achieved. In fact, several cases exist in which the implementation of poorly designed feedback control strategies have actually reduced the tonnage of saleable clean coal.

Incremental Quality Concept

The optimum operating points for different coal preparation circuits are those that maximize overall plant yield at a given clean coal quality. Depending on the liberation characteristics of the feed coal, this may or may not require identical product qualities for each circuit. A common method used to identify these optimum points is to sweep through all possible operating conditions for each circuit and to select the combination that provides the highest yield at the desired quality (Peng and Luckie, 1991). Although workable, this hit-and-miss approach may not be applicable for on-line control purposes and provides little insight regarding the underlying principles that impact plant performance.

A more attractive method for plant optimization is the concept of *constant incremental quality*. This concept, which has long been recognized in the coal preparation industry (Mayer, 1950; Dell, 1956; Rayner, 1987), states that the clean coal yield for parallel operations is maximum when all circuits are operated at the same incremental quality. Incremental quality (Q^*) may be conceptually defined as the quality of the last increment of mass added to a given product when the yield is increased by an infinitesimal amount. Mathematically, incremental quality (Q^*) is given by:

$$Y(Q) + \Delta Y(Q^*) = (Y + \Delta Q)(Q + \Delta Q) \quad \text{(EQ 3)}$$

$$Q^* = \frac{(Y + \Delta Y)(Q + \Delta Q) - Y(Q)}{\Delta Y} = Y\frac{\Delta Q}{\Delta Y} + Q + \Delta Q \approx Y\frac{\Delta Q}{\Delta Y} + Q \quad \text{(EQ 4)}$$

in which ΔY and ΔQ are the infinitesimal increases in the product yield (Y) and quality (Q), respectively (Abbott, 1982).

The mathematical proof of the incremental quality concept is relatively straightforward for a simple two-circuit plant. According to Eq. 1, the combined yield quality can be determined from:

$$Y = S_1Y_1 + S_2Y_2 \quad \text{(EQ 5)}$$

The expression for Y can be maximized by taking the derivative of Y with respect to Y_1 and setting the result equal to zero. This gives:

$$\frac{\partial Y}{\partial Y_1} = S_1 + S_2\frac{\partial Y_2}{\partial Y_1} = 0 \text{ or } \frac{\partial Y_2}{\partial Y_1} = -\frac{S_1}{S_2} \quad \text{(EQ 6)}$$

Likewise, Eq. 2 can be used to determine a second governing expression for Y, i.e.:

$$Y = S_1Y_1 + S_2Y_2 \quad \text{(EQ 7)}$$

This expression can be maximized by taking the derivative of Y with respect to Y_2 and setting the result equal to zero. This gives:

$$\frac{\partial Y}{\partial Y_2} = \frac{S_1}{Q}\left(Y_1\frac{\partial Q_1}{\partial Y_2} + Q_1\frac{\partial Y_1}{\partial Y_2}\right) + \frac{S_2}{Q}\left(Y_2\frac{\partial Q_2}{\partial Y_2} + Q_2\right) = 0 \quad \text{(EQ 8)}$$

$$-\frac{S_1}{S_2}\left(Y_1\frac{\partial Q_1}{\partial Y_2} + Q_1\frac{\partial Y_1}{\partial Y_2}\right) = Y_2\frac{\partial Q_2}{\partial Y_2} + Q_2 \quad \text{(EQ 9)}$$

Substituting Eq. 6 gives:

$$Y_1\frac{\partial Q_1}{\partial Y_1} + Q_1 = Y_2\frac{\partial Q_2}{\partial Y_2} + Q_2 \text{ or } Q_1^* = Q_2^* \quad \text{(EQ 10)}$$

Eq. 10 states that each circuit should be operated at the same incremental quality to maximize yield. This condition is true for any number of parallel circuits and is independent of the size and washability characteristics of the feed coal. For the metallurgical market, this expression normally dictates that all circuits should be operated at the same dry incremental ash in order to maximize the yield. For the utility market, all circuits

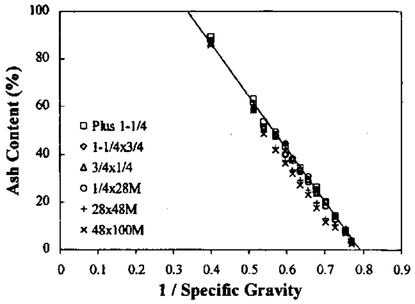

FIGURE 1 Relationship between incremental ash and specific gravity for different size fractions of a typical run-of-mine coal

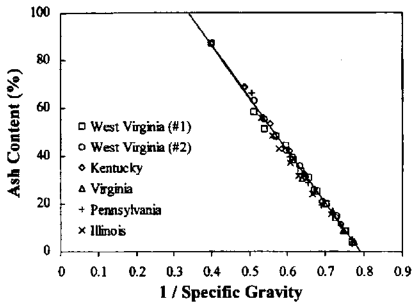

FIGURE 2 Relationship between incremental ash and specific gravity for plus ½-inch bituminous coal samples from five different states

should be operated at the same incremental inerts (ash plus moisture) to maximize the net heating value delivered to power plants.

Ideal Separations

There is currently no technique for the on-line measurement of incremental quality. However, this value can be estimated for ideal separations if the quality parameter is ash. This technique is based on the assumption that run-of-mine coals contain only two components, i.e., a low-density, ash-free carbonaceous component and a high-density, pure-ash mineral component. As such, the ash content of a given particle must increase linearly with the reciprocal of particle density (ρ) according to the expression:

$$\text{Ash (\%)} = \left(\frac{100\rho_2\rho_1}{\rho_2 - \rho_1}\right)\frac{1}{\rho} + \left(\frac{100\rho_2}{\rho_2 - \rho_1}\right) \qquad \text{(EQ 11)}$$

where ρ_1 and ρ_2 is the density of the light (carbonaceous) and dense (mineral) components, respectively (Anon., 1966). A detailed analysis of this problem has been presented by Abbott and Miles (1990).

The suitability of Eq. 11 in predicting incremental ash can be evaluated from the ash contents of narrowly partitioned density fractions of coal obtained from standard float-sink tests. For example, these values are plotted in Figure 1 for six different size fractions of a run-of-mine coal. For particles coarser than 28 mesh, the data show that the same incremental ash is obtained for a given specific gravity regardless of the size fraction treated. The deviation noted for the fractions finer than 28 mesh can normally be attributed to inefficiencies in the experimental float-sink procedures. In addition, Figure 2 shows that this relationship is valid for run-of-mine coal samples from different seams in five different states. In fact, field data collected to date suggest that three different linear relationships may be obtained for bituminous coals of different rank (i.e., high-, medium- and low-volatile matter contents) due to the density variations in the carbonaceous matter. The presence of disproportionate amounts of pyrite in some coal fractions has also been known to create minor deviations from the linear relationship at higher densities. The impacts of these factors on the validity of Eq. 11 must be evaluated on a case-by-case basis.

As noted previously, the incremental quality concept states that plants constrained by an upper limit on clean coal ash may be optimized by operating all parallel circuits at the same incremental ash. Since Eq. 11 implies that incremental ash is fixed by specific gravity, this concept can now be extended to state that plant performance can be optimized by operating all circuits at the same specific gravity cutpoint (Clarkson, 1992). This statement is true regardless of the size distribution or washability characteristics of the feed coal, provided ideal separations are maintained in each circuit. Furthermore, this concept is valid not only for a fixed point in time, but also for the entire duration of a given production cycle. As such, a plant that raises and lowers specific gravity cutpoints for quality control purposes will always produce less clean coal than a plant that maintains the same cutpoints. Obviously, this realization has tremendous implications in the formulation of a plantwide control strategy.

Misplaced Material

Plant optimization would be relatively straightforward were it not for the presence of misplaced particles. A plant equipped with ideal separators could achieve optimum performance simply by maintaining the same specific gravity cutpoint in parallel circuits. Unfortunately, this approach must be modified since ideal separators do not exist in practice. In general, efficiencies of density-based separators tend to decline as the particle size decreases and particle population increases. Misplaced particles have the effect of lowering the incremental ash of a product generated at a particular specific gravity. This is because the mass present in typical run-of-mine coals increases with decreasing specific gravity in the region where most industrial separations occur (i.e., below $\approx$1.7 SG). Consequently, a greater proportion of lower density middlings is misplaced into the reject stream than higher density middlings into the clean coal stream. The unbalanced shift of these higher quality (lower ash) lowers the incremental ash. Therefore, less efficient circuits must be operated at a higher specific gravity cutpoint in order to maintain the same effective incremental quality (Clarkson, 1992).

The impact of inefficiencies on the selection of optimum circuit cutpoints can be studied using a variety of mathematical techniques. The most common approach is to convert the "ideal" separation curves obtained from standard characterization tests (e.g., float-sink tests) into "actual" separation curves. This conversion can be accomplished using either empirical partition models (Armstrong and Whitmore, 1982; Rong and Lyman, 1985) or phenomenological process models (King, 1999). The optimum cutpoints can then be identified graphically by ensuring that all separations are performed at the same slope on a standard M-curve. This graphical optimization technique was originally developed by Mayer (1950) and advocated more recently by King (1999). However, sensitivity studies indicate that this graphical technique of derivative estimation can introduce significant errors in the identification of optimum circuit cutpoints (Lyman, 1992). A simpler approach is to use one of several plant simulation programs that are now commercially available for this purpose. In addition, many of the advanced spreadsheet programs equipped with built-in optimization routines make such calculations relatively easy for even complicated plant circuits.

Figure 3 shows the results of a typical set of spreadsheet simulations conducted for a plant incorporating only a dense medium vessel and a dense medium cyclone (DMC) circuit. In each case, the total plant yield was determined while maintaining a fixed total plant ash of 7.5%. The plant yield was plotted as a function of the cutpoint differential defined as the difference in specific gravity cutpoints (SG_{50}) between the DMC and vessel circuits. The impact of misplaced material was evaluated by varying the cyclone Ep

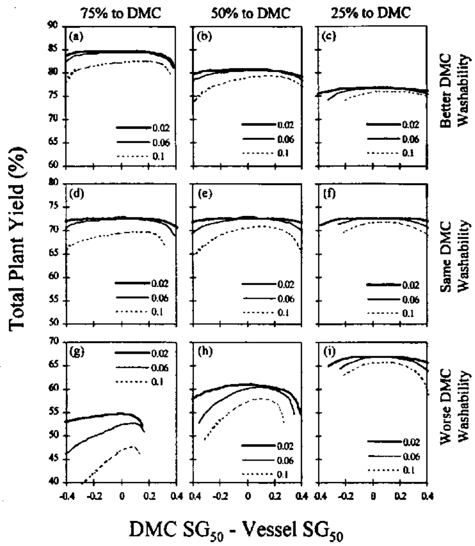

FIGURE 3 Effect of cutpoint differential on total plant yield for different values of Ep, feed mass split and feed washability

TABLE 1 Cutpoint differential (DMC SG_{50} – Vessel SG_{50}) required to maximize plant yield at a constant plant ash of 7.5% (vessel Ep = 0.02)

DMC Washability	DMC Ep	Vessel/Cyclone Mass Split (%)		
		25/75	50/50	75/25
Less Difficult than Vessel	0.02	0.003	0.002	0.002
	0.06	0.064	0.060	0.056
	0.10	0.171	0.159	0.139
Same as Vessel Circuit	0.02	0.000	0.000	0.000
	0.06	0.068	0.055	0.045
	0.10	0.142	0.118	0.078
More Difficult than Vessel	0.02	0.003	0.000	0.000
	0.06	0.094	0.075	0.072
	0.10	0.104	0.087	0.083

from 0.02 to 0.10, while holding a constant vessel Ep of 0.02. Note that a higher Ep value represents a less efficient separation. The simulations were repeated for percentage mass splits between the vessel and DMC circuits of 25/75, 50/50 and 75/25. In addition, the impact of differences in feed coal type was examined by conducting the DMC simulations using three different feed washabilities. For comparison, the cutpoint differentials corresponding to the peak yields are summarized in Table 1.

The data shown in Figure 3 and summarized in Table 1 illustrate the importance of the incremental quality concept. In cases involving efficient separators (i.e., Ep = 0.02), maximum plant yield occurred when the cutpoint differential was near zero. This suggests that efficient separators should be operated at the same specific gravity cutpoint irrespective of the washability characteristics of the feed coal and the percentages of mass reporting to each circuit. This conclusion is equally valid for (i) two separators producing a combined product at a single point in time or (ii) a single separator whose product will be combined over an extended production period. In addition, the simulation

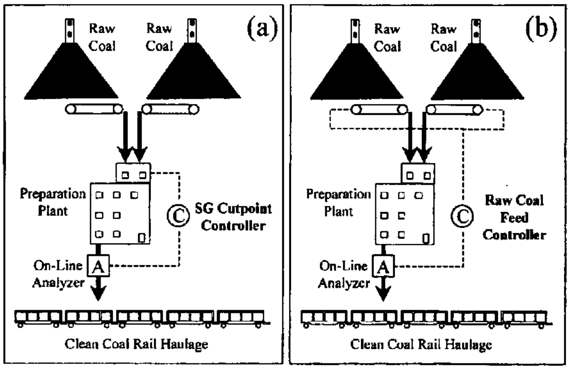

FIGURE 4 Alternative strategies for controlling clean coal quality by (a) manipulation of circuit specific gravity cutpoints and (b) adjustments of feed coal blends

data show that a larger cutpoint differential (i.e., larger DMC cutpoint) is required to maintain optimum yield as the efficiency of the DMC circuit is reduced. Close inspection of the data indicates that the required differential is more sensitive to changes in Ep than to changes in mass split or feed washability. This suggests that the characteristics of the separator are more important in controlling incremental quality than those of the feed material. A theoretical analysis that supports this conclusion has been presented previously by Lyman (1993).

PLANT CONTROL STRATEGIES

The preceding discussion suggests that plantwide performance can be optimized by maintaining constant incremental qualities in all parallel circuits at all times irrespective of variations in the characteristics of the feed coal. As such, this concept does not support the traditional plant control strategy that utilizes feedback from on-line analyzers to make real-time adjustments to circuit cutpoints (see Figure 4a). While this approach improves the consistency of the clean coal quality, it does not optimize plant yield. On the other hand, circuits operated under constant incremental quality will optimize yield, but will often generate clean coal products of highly variable quality. In many cases, the resultant variability will not be acceptable to downstream customers.

An attractive solution to the variability problem is to blend the feed coals just prior to washing. In this control strategy, different feed coals are stored in separate feed stockpiles according to their washability characteristics (see Figure 4b). This is possible since more than one coal supply is often available for most large-scale cleaning plants. Based on feedback from an on-line analyzer, different ratios of coal from the piles are then fed to the plant as required to maintain a constant clean coal quality for the overall plant. This approach allows the quality of the clean coal to be adjusted on-line without changing the predetermined cutpoints that optimize plant performance. Furthermore, precise determination of the washability characteristics of the different coal feeds is not required since the control scheme determines the required mix ratios in real time. The feed coals simply need to be sorted into piles with "better" and "worse" washabilities. The added advantage of this approach is that the plant sees a relatively constant feed washability, which avoids overloading of individual circuits and allows overall plant capacity to be maximized. Unfortunately, the potential exists for one of the stockpiles to be depleted if long-term changes in the coal washability occur. In this case, a supervisory control

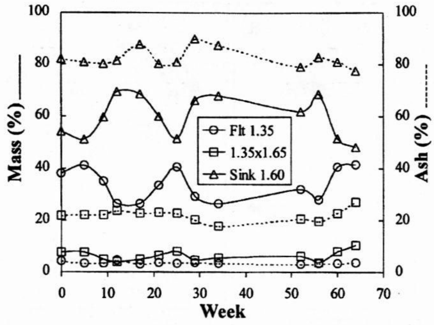

FIGURE 5 Variations in the washability caharacteristics of the plus 6.35 mm fraction of the case study coal

scheme may be used to adjust the plant cutpoint. For example, if the "better" coal is completely consumed, the cutpoint must be lowered and yield sacrificed to maintain a constant product quality. Alternatively, the system could be designed to issue an alarm to the plant operator who could choose to maintain the same cutpoint and ship the lower quality coal to a different market. In any case, the goal of this particular control scheme is to absorb short-term changes in coal washability through variations in stockpile levels without requiring a change in circuit cutpoints.

CASE STUDY

The feed to a coal preparation plant may be subject to significant variations in terms of size, quality and mineralogical association. Factors responsible for these variations include fluctuations in seam characteristics, modifications in mining practices and changes in the mix of coal entering the plant from multiple sections and/or mines. These disturbances make it difficult for plant operations to maintain a consistent coal quality and to maximize clean coal production. In order to examine the extent of these variations, samples were collected from the feed stream to an industrial preparation plant and subjected to washability (float–sink) analyses. The plant samples were taken daily and then combined to prepare a composite feed sample at the end of each four-week period. This procedure was continued for a period of about 13 months. Each sample was sized at 6.35 mm (1/4 inch) and 1 mm (16 mesh). Due to the large amounts of material involved, a two-point float–sink procedure was used for each size fraction. This allowed three specific gravity fractions (i.e., float 1.35, 1.35 × 1.65 and sink 1.65) to be produced for each of the two coarser size fractions (i.e., plus 6.35 mm and 6.35 × 1 mm).

Figure 5 shows the mass yield and ash content obtained for the plus 6.35 mm size fraction. As shown, the percentage of low-ash float 1.35 SG material in the composite feed samples varied substantially from a maximum of 41.4% to a minimum of 26.2% during the sampling campaign. Likewise, the percentage of high-ash 1.65 SG sink material in the composite samples mirrored the data for the float 1.35 SG fraction. The large variations in washability were surprising since each sample was prepared as a composite of approximately 20–25 individual daily samples taken over each four-week sampling period. Consequently, the variations in washability for the individual samples are expected to exceed these average variations. Statistical analyses suggest that standard deviations for the individual daily samples would be in the order of 28.8%, 9.1% and 37.0% for the float 1.35, 1.35 × 1.65 and sink 1.65 SG classes, respectively. It is also

TABLE 2 Simulation of a control system configured to maintain constant product ash via adjustment of individual circuit cutpoints

	Plus 6.25 mm		6.25 mm x 16 M		Overall Product	
Coal Feed	Clean (tph)	Ash (%)	Clean (tph)	Ash (%)	Clean (tph)	Ash (%)
Poor	75.5	5.00	197.2	5.00	272.8	5.00
Good	124.2	5.00	222.6	5.00	346.8	5.00
Blend	99.9	5.00	209.9	5.00	**309.8**	**5.00**

TABLE 3 Simulation of a control system configured to maintain constant product ash via adjustment of coal feed blends

	Plus 6.25 mm		6.25 mm x 16 M		Overall Product	
Coal Feed	Clean (tph)	Ash (%)	Clean (tph)	Ash (%)	Clean (tph)	Ash (%)
Poor	74.8	4.82	190.2	3.85	265.1	4.12
Good	137.6	6.29	226.1	5.25	363.7	5.64
Blend	106.2	5.77	208.1	4.61	**314.4**	**5.00**

interesting to note that the variations in the washability of the 6.35 × 1 mm size fraction were less prominent. The standard deviations for these daily samples were estimated to be 14.9%, 4.0% and 12.5% for the float 1.35, 1.35 × 1.65 and sink 1.65 SG classes, respectively. The smaller variability may be attributed to the improved liberation of the finer material.

In order to evaluate the potential benefits of the proposed analyzer, a series of plant simulations were performed for the processing of the plus 6.35 mm and 6.25 × 1 mm size fractions. A combined plant feed rate of 750 tph was assumed for these two sizes and a clean coal ash content of 5% was targeted. The simulations were performed using "poor" and "good" plant feeds determined from statistical analyses of the plant data. A regression routine developed as part of this project was used to expand the washability data into classes between 1.2 SG and 2.2 SG in increments of 0.10 SG units. As expected, the simulation data showed that it was impossible to maintain a constant product ash content as the plant feed varied between good and poor washabilities. Therefore, simulations were performed to evaluate the effectiveness of a control system that employs a traditional on-line ash analyzer to maintain a constant product ash in all circuits via on-line adjustment of circuit cutpoints. This control strategy allowed 309.8 tph of blended clean coal to be produced at 5% ash (see Table 2). Simulation runs were also performed to determine the performance that may be achieved by maintaining fixed cutpoints and adjusting quality via feed coal blending. In this case, 314.4 tph of clean coal were produced at 5% ash (see Table 3). The net difference between the "cutpoint-based" and "blend-based" control schemes is about 4.6 tph of additional clean coal. For a metallurgical coal sold at $36.50/ton, this represents in excess of $1 million in revenues annually (i.e., revenue = 4.6 ton/hr × $36.50/ton × 6,000 hr/yr = $1,007,400/yr).

CONCLUSIONS

A theoretical principle known as the incremental quality concept provides useful insight concerning the optimization of coal preparation plants. According to this concept, a plant limited by an upper constraint on clean coal quality will produce maximum total yield when all parallel circuits are operated at the same incremental quality. This requirement is met when efficient circuits are operated at the same specific gravity cutpoints, while less efficient circuits need to be operated at slightly higher cutpoints to correct for the increased misplacement of coal middlings. The optimum cutpoints can be readily identified using mathematical simulations and remain relatively fixed irrespective of small variations in the size and washability characteristics of the feed coals. Furthermore, this concept applies not only for a fixed point in time, but also for the entire duration of a given production cycle. Therefore, the incremental quality concept supports (i) operation at fixed specific gravity cutpoints and blending of feed coals before washing to maintain product consistency and (ii) the on-line measurement of clean coal quality to adjust feed blends. This concept does not support the real-time adjustment of specific gravity cutpoints based on on-line measurements of product quality. A plant that raises and lowers specific gravity cutpoints to maintain constant quality will always produce less clean coal than a plant that maintains the same cutpoints. Data obtained from a case study indicate that additional revenues of approximately $1 million annually are possible through the implementation of feed blending for plant control.

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