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CONTROLLER IMPLEMENTATION TO IMPROVE PHOSPHATE RECOVERY AT PCS PHOSPHATE'S SWIFT CREEK MINE

Prepared by
BCD Technologies

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March 2004

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CONTROLLER IMPLEMENTATION TO IMPROVE PHOSPHATE RECOVERY AT PCS PHOSPHATE'S SWIFT CREEK MINE

FINAL REPORT AND ADDENDUM

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March 2004

DISCLAIMER

PERSPECTIVE

Patrick Zhang, Research Director - Beneficiation & Mining

There is an ever-present need for the phosphate industry to continually improve productivity, resource utilization, and overall efficiency. One of the most effective approaches to achieve a significant improvement is the real-time control of each of the unit operations. Process control systems routinely used in mineral processing were born with the invention of the microprocessor. It is expected that control systems of future will continue to develop towards user-friendly computer-based systems which use powerful software analysis and control techniques.

The Florida phosphate industry has been practicing the current flotation technique for half a century. However, process control in most, if not all, of the beneficiation plants is somewhat primitive. This situation has been attributed to three major factors: lack of on-stream, rapid chemical/mineralogical analysis; lack of reliable unit operation models; and fluctuation of feed characteristics. FIPR has directed extensive research efforts at evaluating on-stream analytical techniques, one of which (the NMR Phospholyzer) has been commercialized. The next logical step would be to develop control strategies in such a way that the instant on-line information may be utilized for process control.

Under a previous FIPR project entitled “Optimizing, Adaptive Process Control for Phosphate Flotation” (FIPR #96-02-123), BCD Technologies concluded that the powerful neural network might not be the best tool for process control of phosphate flotation. Side-by-side comparison with plant operation showed that the adaptive control strategy using fuzzy logic and genetic algorithms did not do much better than plant operators. However, BCD Technologies discovered a simple control curve that could maintain flotation recoveries of over 90% if implemented on commercial scale. Countless simulation calculations showed that the ratio of flotation feed grade (% BPL) to fatty acid flowrate correlates well with flotation performance. The current project was designed to install a computer control system that implements a “Control Curve Approach” to process control.

The Control Curve Approach has been implemented and evaluated at an operating plant, achieving significant reduction in fatty acid usage without sacrificing grade and recovery. With some on-line analytical information, this approach seems to perform at least as well as an experienced operator. Before a more sophisticated and powerful control system is developed, this method is worth trying, since it is so inexpensive.

This report was originally completed and ready for publication in 2003, but at the request of the contractor it was withheld until extended testing of the Control Curve Approach at the PCS Swift Creek Mine could be completed. The results of this extended testing are contained in the addendum to the report.

ABSTRACT

This report describes a straightforward algorithm or approach for controlling phosphate processing plants. The approach described, termed the "Control Curves Approach," relies on *a priori* analysis of large amounts of operating data from the plant. The PCS Phosphate's Swift Creek Mine outside of Lake City, FL was almost ideally suited for this task due to the existence of an MNR and associated data acquisition system. The data for the current study was collected over several months, then analyzed using spreadsheet macros written specifically for the task. This data analysis is straightforward and critical to the development of the Control Curves Approach. Upon completion of the data analysis portion of the development, the Control Curves Approach is easily encapsulated in a few spreadsheet commands implemented in the form of macros. This report describes the Control Curves Approach, presents its implementation in a computer spreadsheet, and describes the results of implementing the control system at PCS Phosphate's Swift Creek Mine plant. Results indicate that the Control Curves Approach allows for plant recoveries equitable to those achieved by human operators. However, the Control Curves Approach achieved its level of performance while utilizing far less conditioner than required by the human operators to achieve the same levels of performance.

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EXECUTIVE SUMMARY

Phosphate flotation plants in the United States are not currently operating at peak performance. This inadequacy must be rectified if the United States is to continue competing in the world market. The biggest improvements in the efficiency of existing phosphate processing plants in the near future are likely to be made by implementing new and improving computer-based process control systems. On the other hand, it is imperative that computer control systems implemented in phosphate processing plants are straightforward, easily implemented, and easily maintained.

In a recently completed FIPR project entitled "Optimizing, Adaptive Process Control for Phosphate Flotation," a straightforward, yet unique approach to obtaining and maintaining efficient operating conditions in a phosphate flotation plant was alluded to. This approach, termed the "Control Curves Approach," is the focus of the current study. Specifically, the approach is developed, implemented on a computer spreadsheet, installed, tested, and evaluated at an operating plant – PCS Phosphate's Swift Creek Mine outside of Lake City, Florida.

The Control Curves Approach relies on a priori analysis of large amounts of operating data from the plant. The Swift Creek Mine plant was almost ideally suited for this task due to the existence of an MNR and associated data acquisition system. The data for the current study was collected over several months, then analyzed using spreadsheet macros written specifically for the task. This data analysis, although sometimes precarious due to periods in which either the MNR or the data acquisition system is down, is straightforward and critical to the development of the Control Curves Approach.

Upon completion of the data analysis portion of the development, the Control Curves Approach is easily encapsulated in a few spreadsheet commands implemented in the form of macros. Although the Control Curves Approach could well be implemented in virtually any computer programming language, spreadsheets were selected as the implementation environment because they: (1) are easy to develop and maintain, (2) are capable of communicating with virtually all data acquisition systems, (3) are familiar to most plant engineers, and (4) are cost effective. An effective computer interface was developed to facilitate implementation of the Control Curves Approach.

The culmination of the current project involved implementing the Control Curves Approach to process control at the PCS Phosphate's Swift Creek Mine plant. Results from this effort indicate the Control Curves Approach is effective. Recoveries achieved by the Control Curves Approach were equitable to those achieved by human operators for identical plant conditions. However, the Control Curves Approach achieved its level of performance while utilizing far less conditioner than required by the human operators to achieve the same performance levels. The details of this study are summarized in the remainder of the report.

OBJECTIVE

The objective of the current project was to develop, install, and evaluate a computer control system that implemented a Control Curves Approach to process control. This approach was initially alluded to in a previous FIPR project entitled, "Optimizing, Adaptive Process Control for Phosphate Flotation." In that particular study, the goal of BCD researchers was to develop an adaptive, model-following control system for efficiently operating a phosphate flotation plant. Despite BCD's success in developing and implementing the adaptive, model-following controller, post-installation analysis indicated that the computer software had some requirements that made its success an iffy proposition. Specifically, the software required either a detailed level of understanding of several computational techniques (a level of understanding not likely to be developed by busy plant engineers), or an on-site computer specialist familiar enough with the software to occasionally make changes. Since phosphate processing plants were unlikely to successfully maintain the adaptive, model-following control system in their operating plants, a simpler approach has been adopted.

In their earlier effort described above, BCD researchers alluded to a simple yet potentially effective approach to achieving effective control of the plant by using a Control Curves Approach. This approach strips away layers of complexity contained in volumes of data taken (yet seldom fully analyzed) with modern data acquisition systems. Through some simple statistical and graphical analysis of plant data, BCD researchers were able to develop a straightforward strategy for achieving effective process control. This strategy is easily implemented using computer spreadsheets—the plant engineer's tool of choice.

The objective of the current study is to fully develop the Control Curves Approach in a computer software tool, implement the approach in PCS Phosphate's Swift Creek Mine processing plant, and evaluate the performance of the Control Curves Approach.

INTRODUCTION

In a recent completed FIPR project entitled "Optimizing Adaptive Process Control for Phosphate Flotation," an adaptive controller using a neural network was developed. In simulations using plant data, the controller preformed equal to the plant's operators. As an outcropping of this work a "control curve" was developed using plant data, and ultimately a control strategy based on the "control curve" was suggested that in simulations suggested recoveries in the 90% range could be consistently achieved. In the current effort a controller based upon this Control Curve Approach was installed at the PCS Phosphate Swift Creek Mine location. This research was a joint venture between BCD Technologies, PCS Phosphate, and The University of Alabama (via the use of student programmers). However, despite the fact that this research project was performed at PCS Phosphate, special care was taken to ensure that the system developed is flexible enough to be easily implemented at other plants that have simple data acquisition systems.

LITERATURE REVIEW

In the final report of the project "Optimizing Adaptive Process Control for Phosphate Flotation" (Karr and Scheiner 2000) it was suggested that recoveries in the 90% range could be obtained with proper computer-based process control. Based upon thousands of data sets, a series of control curves were developed for a specific processing line, under given operating conditions. The control curve was then evaluated by using different plant data. Results in computer simulations showed that in fact the recoveries were in the range predicted, and conditioner usage was markedly reduced. To adequately test this Control Curves Approach to process control however, a computer control system must be installed at an operating plant.

To date, the phosphate industry has not fully embraced computer control of the plant. Most operations have a data collection system such as Wonderware or PI, but these systems are generally being used only for data collection, and data evaluation is perhaps performed later--when time permits--to help plant efficiencies for the future. On-line control is not being used; all decisions are in the hands of the operators. It is important to note that there are adaptive control systems that have been successfully demonstrated in a number of industries, like the adaptive control system for helicopter flight control (Phillips, Karr, and Walker 1996). However, these control systems are generally too complex, requiring a computer professional dedicated exclusively to maintenance of the software, a luxury that simply does not exist in the mineral processing industry.

PURPOSE

The purpose of the current investigation is to install a controller at the Swift Creek Mine and demonstrate that the plant can be operated with higher recoveries and reduced conditioner usage. Strategies developed under this project will have application for the entire phosphate industry. The control system installed and evaluated is based upon relationships developed under previous FIPR projects completed by BCD Technologies. The project is a joint effort between BCD Technologies, PCS Phosphate (the Swift Creek Mine location), and The University of Alabama. As part of this project, BCD Technologies in conjunction with The University of Alabama completed the software development and controller installation. PCS Phosphate provided computer technicians, laboratory analysis, and evaluation of plant results in conjunction with BCD's efforts.

METHODOLOGY

During the process of designing, implementing, and testing optimizing, adaptive control systems over several years, a large amount of plant data was collected and analyzed. During this analysis process, some relationships were observed and validated that can potentially be used as a simple alternative to the complex optimizing controllers typically used in aerospace, navigation, and weapons systems. Results presented later in this report demonstrate the cost-effectiveness of implementing the Control Curves Approach in operating plants.

Phosphate processing plants tend to have numerous sub-systems, each of which can be quite complex in their own right. However, fundamentally, the main decision that can generally be made to control the plant is fatty acid addition. And, the appropriate amount of fatty acid addition is generally dependent on the quality and amount of feed coming into the plant. This fundamental relationship is born out in the data analyzed during the course of the project. An attempt has been made to quantify this relationship, and to develop an effective way to utilize this information to control the plant.

The plant at Swift Creek operates very smoothly, and like most operators under these conditions, the Swift Creek operators often leave the fatty acid feed rate the same for considerable periods of time. Analysis of tens-of-thousand of data points where feed BPL, pumping rate, tails, and fatty acid setting were correlated, show that there is a definite relationship that can be used to predict the fatty acid requirements needed to obtain high recoveries. Figure 1 shows a typical plot one can obtain showing that the amount of fatty acid required to obtain greater than 90% recovery changes dramatically as the amount of BPL in the system changes. Figure 2 is a similar plot for just higher grade feed. As can be seen from these two figures, the curves that can be drawn through the points of the graphs provide an operating line that can be used to control the plant.

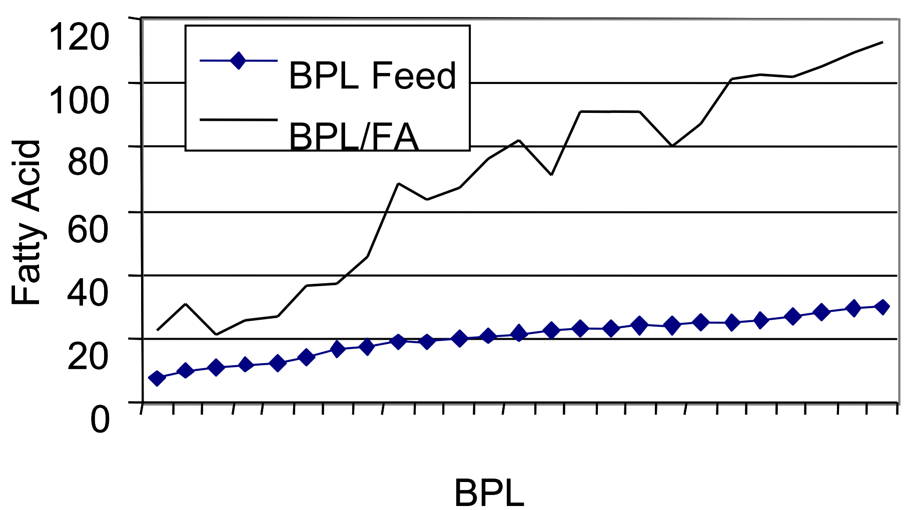

Figure 1. Fatty Acid Versus Low-Range BPL.

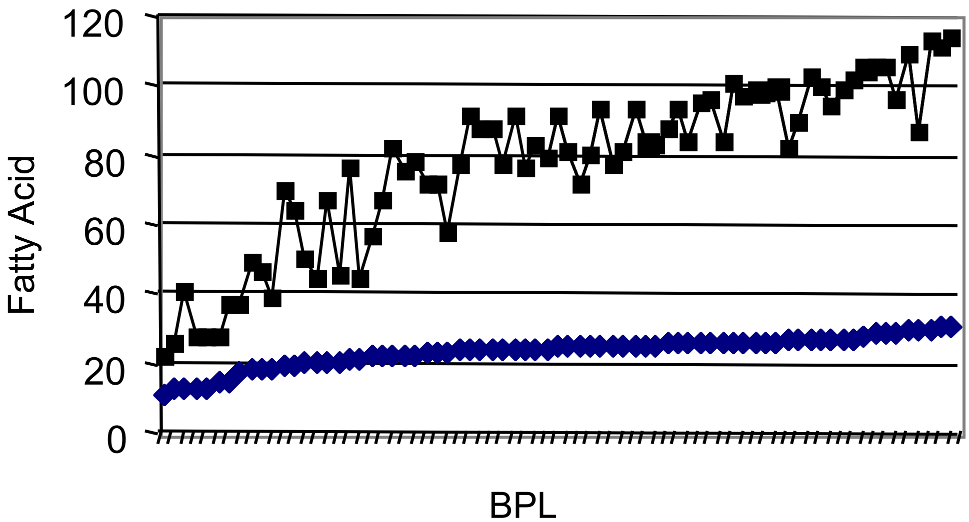

Figure 2. Fatty Acid Versus High-Range BPL.

Another data set was acquired and archived during a period in which the plant was operating efficiently. The recovery of the plant during the time in question is shown in Figure 3. Here it can be seen that during the eighty-minute interval, the plant recovery transitions from values of approximately 88% to values that are consistently above 94%. The feeling is that during this period the plant operators are performing at a high level of efficiency. Thus, the goal is to capture the operators' knowledge and performance characteristics during this period, and to archive this information so that it can be used consistently.

This knowledge is represented in Figure 4 which shows a plot of the feed BPL-to-fatty acid addition over the given time period. Notice that although this plot has some oscillations, it can be represented by a linear relationship (at least in various regions). This curve (or these curves) can be used to compute an effective, if not optimum fatty acid addition. The user can select the correct value of BPL on the x-axis, read up to the curve, and then compute the fatty acid addition. Based upon the above calculations, other data points that were not used before were evaluated and it was found that the BPL/FA were quite similar, usually falling with 5 percent of previous values. This approach could be used in virtually any plant where the plant is running efficiently, i.e., in a stable mode.

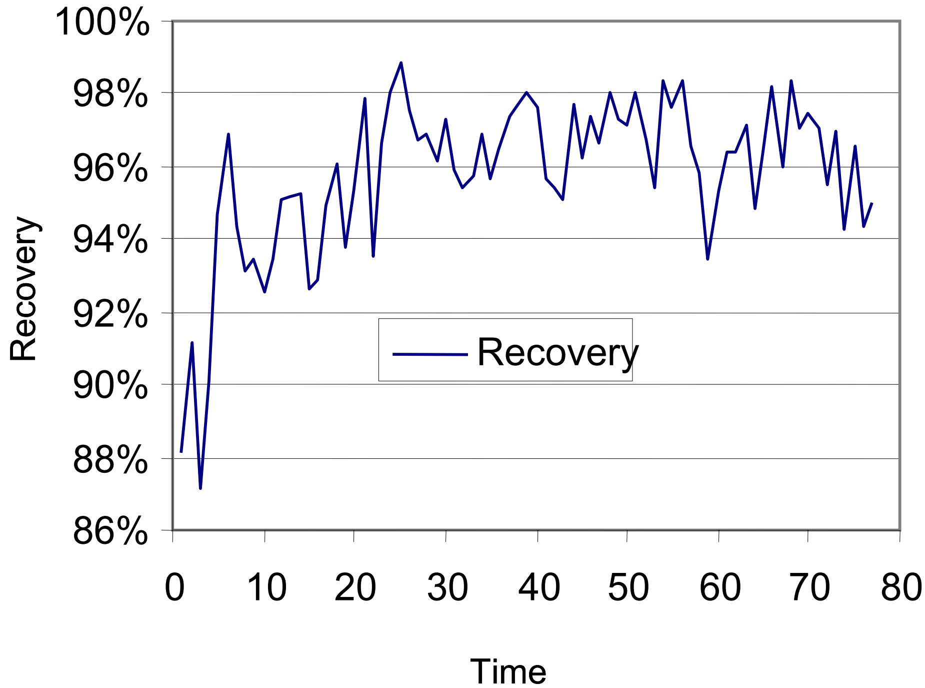

Figure 3. Plant Recovery Versus Time.

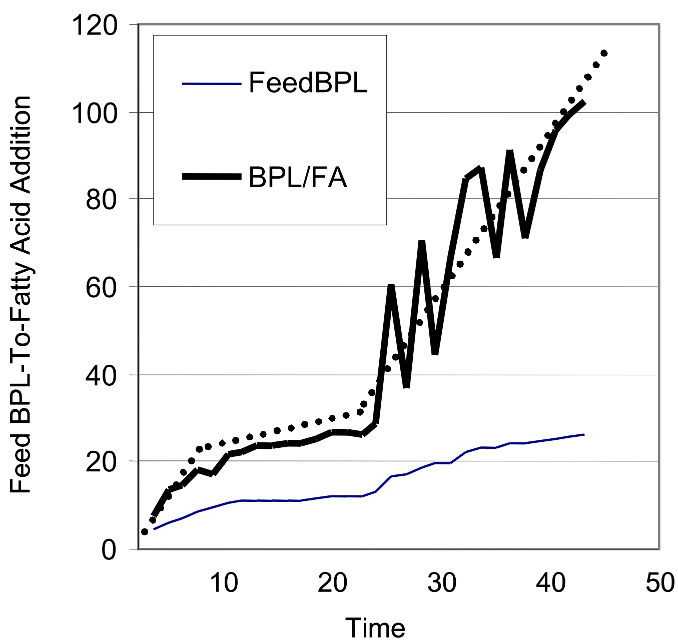

Figure 4. Feed BPL-to-Fatty-Acid Addition.

CAPTURING AN OPERATOR'S KNOWLEDGE

The main idea behind the Control Curve Approach is really to capture the knowledge of the operators running the plant. Like most phosphate processing plants, PCS Phosphate's Swift Creek Mine plant is run efficiently during certain times. This successful operation is due to the fact that the plant is run by operators who have many, many hours of practice in manipulating fatty acid addition for a wide variety of operating conditions. The fundamental premise of the Control Curve Approach is to capture the knowledge of the plant operators (when the plant is running well), encapsulate it into a number of control laws, and apply these control laws consistently.

To gain a better understanding of the approach, consider first the data gathered at the plant: (1) Date and Time, (2) Feed BPL, (3) Tails BPL, (4) Feed TPH (tons per hour), and (5) Fatty Acid Addition. These five values are used in a straightforward calculation of:

(1) BPL ($BPL = feedTPH * FeedBPL$),

(2) Recovery ($Recovery = 1 - \left[\left(\frac{Tails\ BPL}{Feed\ BPL}\right) * 0.67\right]$), and

(3) BPL per Unit Fatty Acid Addition ($BPL\ per\ Unit\ Fatty\ Acid\ Addition = \frac{BPL}{FattyAcid}$).

The 0.67 factor in the equation for recovery represents the ratio of tails produced to the amount of feed. Analyses of the ratio of tails to feed showed that the ratio ranged from 0.63 to 0.73 for a ten day period. For initial study, 0.67 was chosen. Later data analyses using a different ratio, i.e., 0.70, produced a control curve that was shifted only a small amount.

Figure 5 shows values of BPL. Note from this figure that there are periods (points) at which the plant is running well; and, periods when the BPL is not as good as it perhaps could be. This plot is indicative of plant performance, and it is very difficult to draw any conclusions about the effectiveness of the operator's inherent rules based on this data.

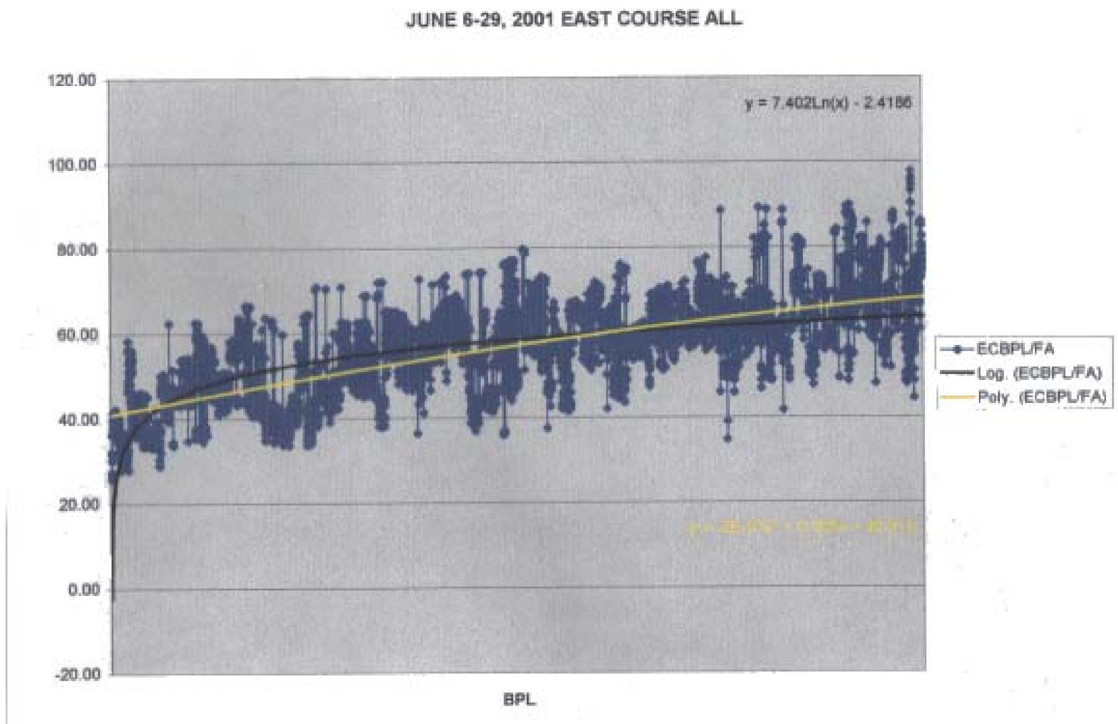

Figure 5. Plant BPL Values.

The real problem with trying to extract rules from the data plotted in Figure 5 is that there is simply too much data to effectively process. Thus, the approach taken here is to use data reduction to try to make sense of the operational strategy used by the operator. All data values are ordered by increasing values of Recovery. Points with recovery of less than 90% are eliminated from the database. The thinking is that the remaining points represent periods in which the plant is running well.

The points in the working database are ordered by increasing values of BPL, and plotted. Figure 6 shows a plot of the working database plotted with BPL Per Unit Fatty Acid Addition versus BPL. Next, a curve is fit to the data, and this curve is considered the Control Curve for the plant. In the figure, the equation of the control curve is $BPLperUnitFA = 12.341 * \ln(BPL) - 26.569$.

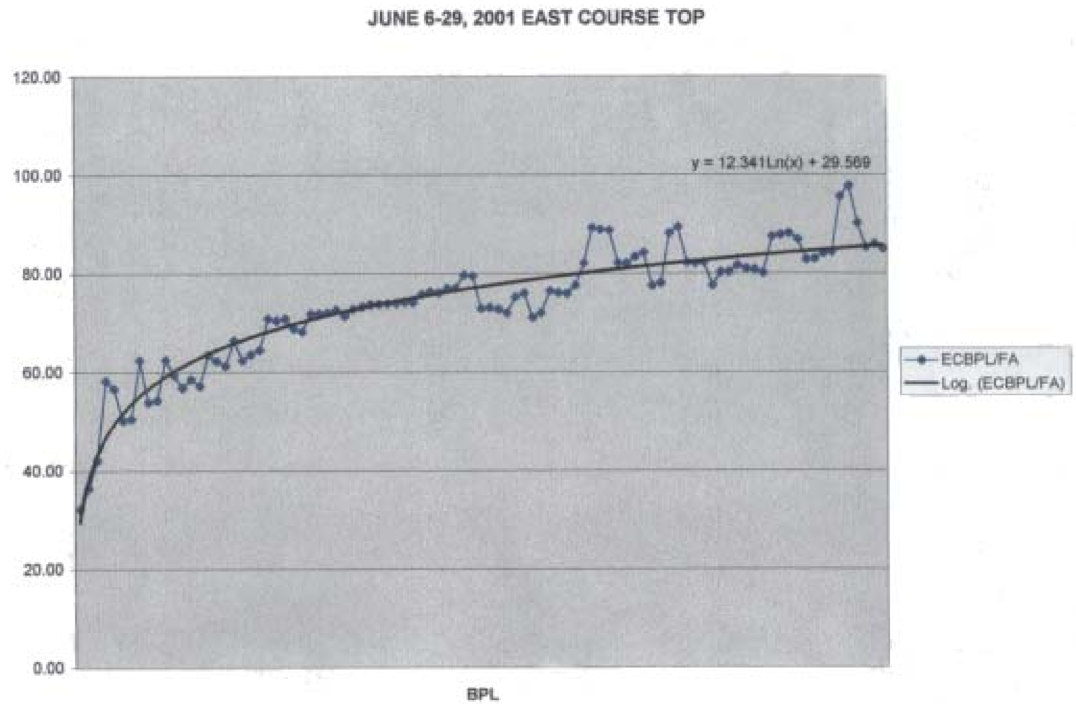

Figure 6. BPL Per Unit Fatty Acid Addition Versus BPL.

The curve shown in Figure 6 is the actual Control Curve for this plant. The Control Curve Equation is used to determine a recommended fatty acid addition for given operating conditions. A new data point is obtained from the MNR in the plant. Given this data, the Control Curve Equation is used to compute a recommended value for the fatty acid addition.

The Control Curve Approach has been explained above. Given a set of data, it is a rather straightforward process to: (1) cull unwanted data points obtained from a data acquisition system, (2) plot the remaining data points, (3) curve-fit the desired operational data points (compute a control curve), and (4) use the control curve to formulate an equation that can be used to manipulate the plant. The next section of this report shows the effectiveness of implementing this approach in an actual phosphate processing plant.

RESULTS

The Control Curve Approach has been developed and implemented via Excel spreadsheets. One of the main concerns with any new computer system is ease of use for the practicing engineer. Although the Control Curve Approach is straightforward, a graphical user interface has been developed to ensure that the software is easy to implement. Figure 7 shows the graphical user interface developed for use in the plant.

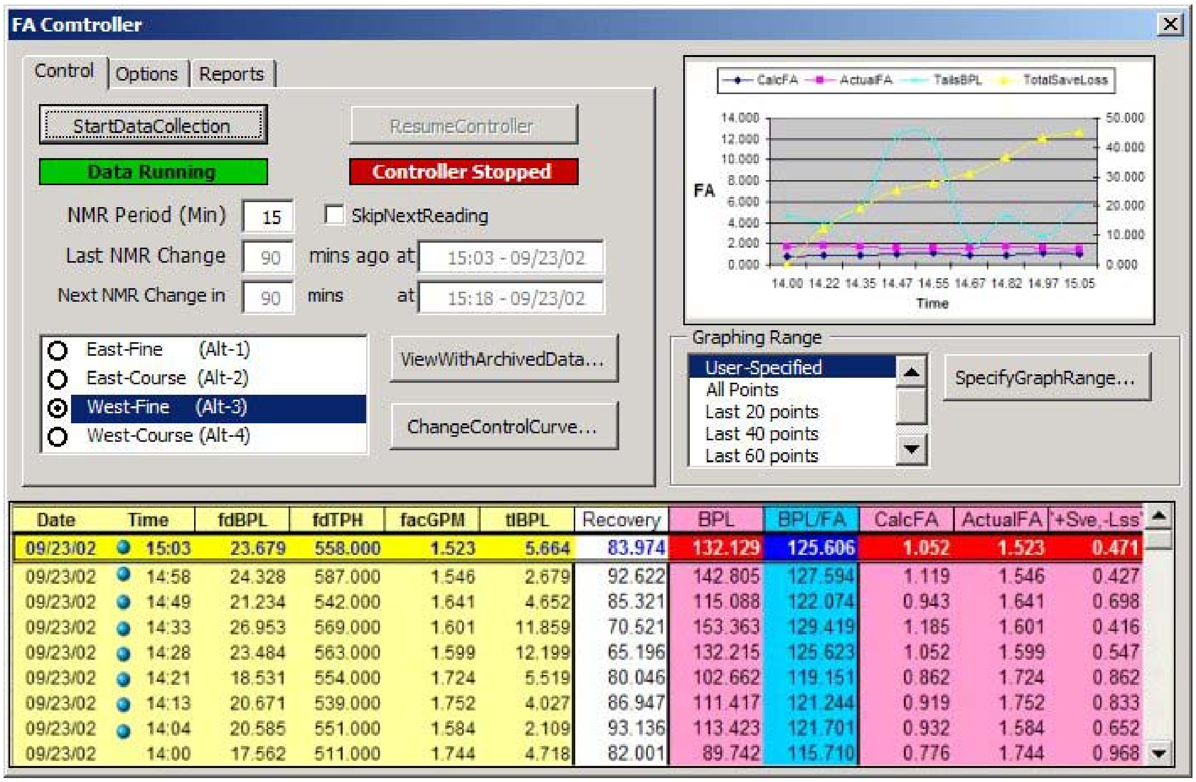

Figure 7. Graphical User Interface.

The Control Curve Approach was initially field tested at the PCS Phosphate Swift Creek Mine in the early Fall of 2002. In this test series, based on feed BPL, the controller would decide on the amount of fatty acid required and the plant operator would lower the fatty acid level toward the recommended amount and operate for a period of time to obtain several NMR readings on the circuit's performance (test usually lasted about an hour). This process was repeated and the fatty acid feed rate would be lowered again, and data collected. For example, let's say that the circuit was operating at 1.8 gallons per minute at the start of the test. The controller calculated that 1.2 gallons per minute was needed, so the controller lowered the feed rate to 1.6 gallons per minute. After about an hour of operating at this level, the fatty acid was lowered again to 1.4 gallons per minute and operated for an hour. The results showed that at the lower fatty acid levels the recovery remained at or above 90%. Tests were performed on different flotation circuits (Swift Creek has four rougher flotation circuits) to demonstrate the robust nature of the approach. When moving to test a different flotation circuit, the feed rate suggested by the controller for the original circuit were typically left unchanged as testing on a new circuit was being performed. These flow rates would be left unchanged for hours, thereby providing results over extended periods of time. Results for these periods were excellent.

Figure 8 provides a summary of the system performance. Note from the curve that fatty acid addition usage was markedly lower when the Control Curve Approach was implemented. In fact, over the one-hour operational period, the Control Curve Approach was able to save almost 13 gallons of fatty acid. Extrapolating over an entire shift, or even over a month or longer, this is a dramatic economic saving to the company; without any loss in performance in recovery (perhaps even improved performance). This approach has the potential to save PCS Phosphate tremendous expense they have incurred due to excessive fatty acid usage.

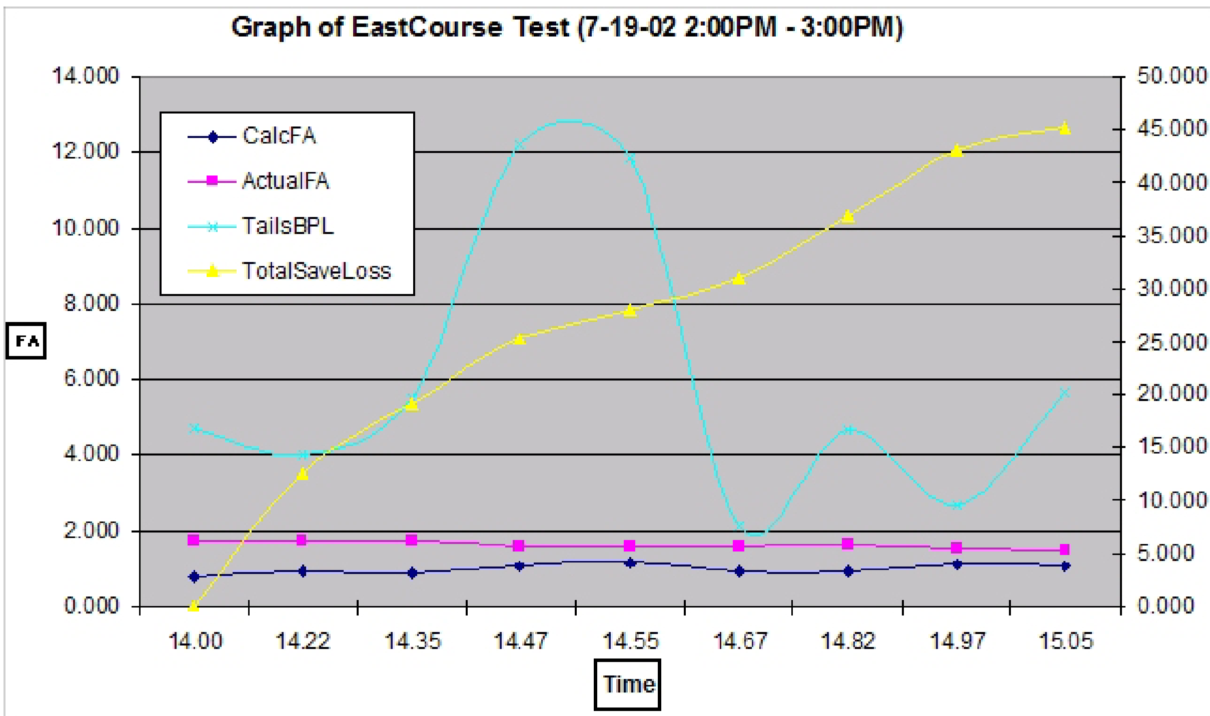

Figure 8. Fatty Acid Addition Versus Time.

The flotation plant at Swift Creek does not do sizing of the feed. So, from time to time a slug of course feed would pass through the flotation circuit. In testing, we observed this phenomenon. For example, during a test the amount of fatty acid was chosen by the controller and the circuits set at a new fatty acid setting. At the next NMR reading, the tails showed 2%, which of course represents a greater than 90% recovery for the BPL being fed to the circuit. The following NMR reading showed that the tails had jumped to 5.8% even though the amount of feed and fatty acid going to the circuit had not changed. Then, the next NMR reading showed a tails of 2%. This indicated that a slug of course material had moved through the circuit. The fact that a course slug had actually passed through the circuit was verified by pulling a physical sample from the circuit for analysis.

It is important to note that Swift Creek plant is relatively stable. The Control Curves, therefore, were computed using data that was considered to be "fairly consistent." Any data sets exhibiting a wide range of variation were not used to construct Control Curves. If the only data available exhibited a wide range of variation, then traditional data smoothing techniques could be used, and the expected results from the resulting Control Curves would be similar to those published in this report.

A second set of Beta tests were run in August 2003. The main objective of the Beta-testing conducted at the Swift Creek Mine during the week of August 11-15, 2003, was to run the Control Curves Approach for extended periods of time. Since the initial test results demonstrated that the control approach was robust enough to effectively manipulate a variety of rougher flotation circuits, the Beta-testing was focused on only two of the four rougher flotation circuits.

The Beta test was conducted according to the following procedure. The controller was used to compute an amount of fatty acid required in the rougher flotation circuit. This value was implemented via a direct link to the automated system, thereby overriding the human operator, who served simply as a safeguard against potential problems. The fatty acid was adjusted toward the recommended fatty acid level, and allowed to operate for a period of time to obtain several NMR readings on the circuit's performance. This process was repeated, the fatty acid feed rate was adjusted again, and data was collected.

The Control Curves Approach was run for extended periods according to the strategy presented above. The circuit was allowed to stabilize then the automated system was invoked and compared to the "normal operating procedures" generally invoked in the plant. This section describes the results of two specific runs that were part of the Beta test.

Beta Test--Example One

Table 1 shows the values obtained from a four-hour run in the Swift Creek plant on August 11, 2003. The values presented in the table are time, tails BPL (to show that the circuit is performing acceptably as described by "grade"), the calculated fatty acid addition as computed using the Control Curves Approach, the operator-prescribed fatty acid addition, and the total savings in fatty acid (since the beginning of the run). These data are also presented in a different form in Figures 9 and 10 below.

In this example, the plant operator controlled the plant for the first hour, the Control Curves Approach was used for the second hour, the plant operator controlled the plant for the third hour, and the Control Curves Approach was again used for the fourth hour.

Note that during the first hour of operation, the tails BPL is varying considerably. There are numerous reasons this can occur, including the fact that the plant feed can come from different draglines, the operator can be attempting to maximize the throughput, etc. During the second hour of operation (Control Curves Approach), the tails BPL is much more stable and the system is using less fatty acid. During the third hour of operation, the operator has the tails BPL stabilized and is using only slightly more fatty acid than prescribed by the Control Curves Approach. During the final hour of operation, the Control Curves Approach is again using less fatty acid, but allows the tails BPL to rise. These results are consistent with the Control Curves Approach which was implemented with the intent of minimizing fatty acid usage.

Table 1. Summary Data from Beta Test.

Control	Time (minutes)	Tails BPL (percent)	Plant Set Fatty Acid (gal/min)	Control Curves Fatty Acid (gal/min)	Total Fatty Acid Savings (gal)
Operator	0:00	3.604	1.788	1.439	
	15:00	8.298	1.842	1.638	
	30:00	4.498	1.768	1.541	
	45:00	2.404	1.759	1.557	
Control Curves	60:00	3.859	1.628	1.232	
	75:00	4.594	1.576	0.923	
	90:00	4.296	1.581	1.198	
	105:00	4.768	1.601	1.542	9.00
Operator	120:00	7.449	1.811	1.648	
	135:00	7.513	1.833	1.733	
	150:00	4.806	1.784	1.632	
	165:00	6.069	1.888	1.542	
Control Curves	180:00	5.738	1.879	1.579	
	195:00	6.187	1.909	1.747	
	210:00	4.551	1.915	1.841	
	225:00	5.383	1.920	1.570	0.00
					9.00

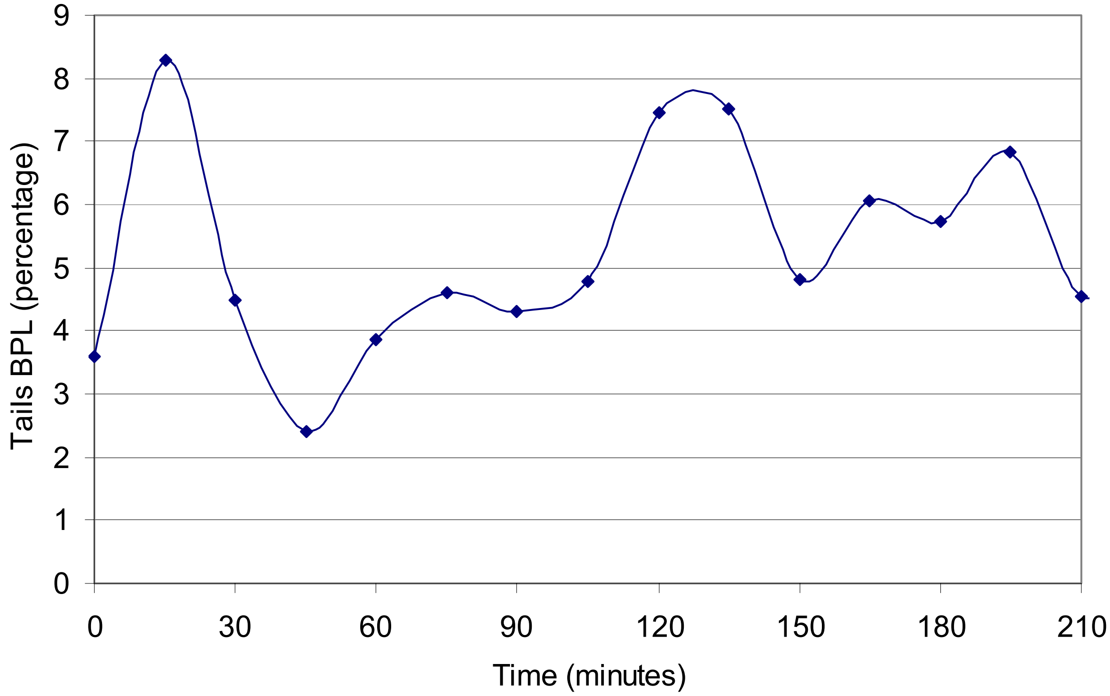

Figure 9. Tails BPL Versus Time.

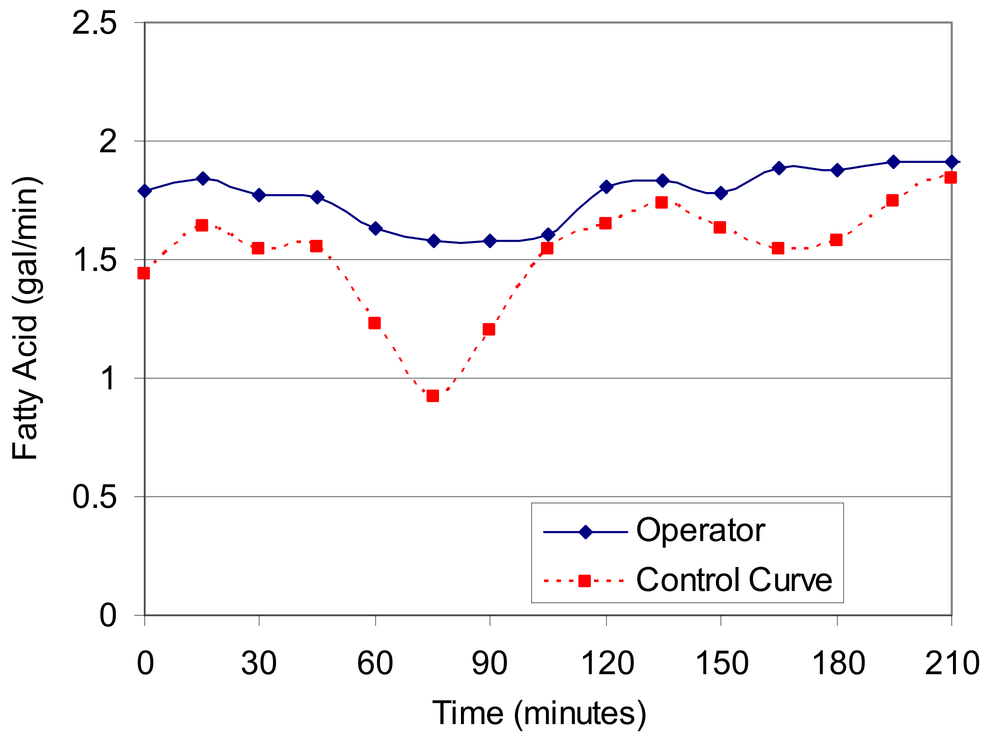

Figure 10. Fatty Acid Addition Versus Time.

An advantage of the Control Curves Approach is that the operator has the ability to manipulate the extent to which the controller focuses attention on the fatty acid addition as opposed to the tails BPL. This fact is depicted in Figure 11 which shows what the fatty acid addition would have been if alternative control curves had been used. In this figure, "Control Curve 1" shows the fatty acid addition prescribed by the system using the control curve actually employed during the test. The other curves represent fatty acid additions that would have been prescribed by the Control Curves Approach had alternative control curves (contained within the computer software) been utilized. Note that the control curve used is the most aggressive with regards to minimizing fatty acid usage. "Control Curve 4," on the other hand, is most aggressive with regard to manipulating the tails BPL. This feature of the software allows the plant operator to focus on various objectives.

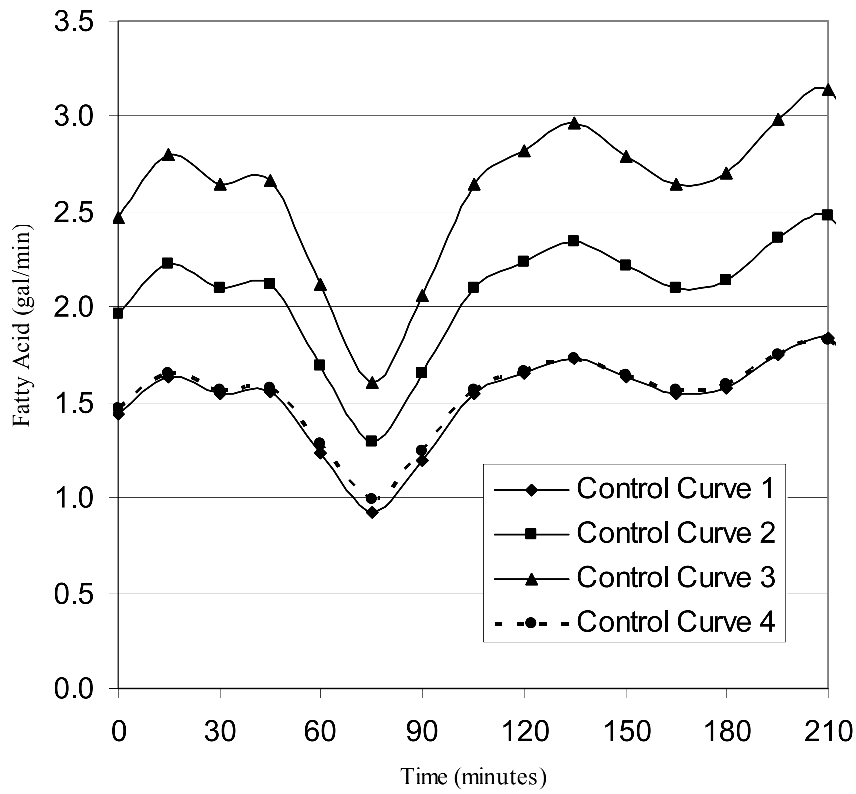

Figure 11. Different Recommended Fatty Acid Additions from Various Control Curves.

This example demonstrates the fact that the Control Curves Approach can actually provide a savings in fatty acid. In addition, it brings to light the fact that different control curves can be employed to achieve varying objectives, e.g., reducing fatty acid addition versus decreasing tails BPL. This flexibility allows the operator to implement a control algorithm consistent with current goals.

Beta Test--Example Two

The second sample test was conducted differently from the first example presented previously. In this example, the operator initially gained control over the system. Then the Control Curves Approach was implemented and allowed to manipulate the fatty acid addition for an extended period. Table 2 shows the results of this effort. In this scenario, it should be clear that it is possible to run the system efficiently while using less fatty acid than typically thought. This data is shown graphically in Figures 12-14. Figure 12 shows the value of the tails BPL as a function of time. Basically the purpose of this figure is to demonstrate that the plant is operating at an acceptable level of efficiency. Figure 13 demonstrates that the Control Curves Approach consistently prescribes a reduced amount of fatty acid. Figure 14 shows the savings in fatty acid that were achieved during the course of the four hour test--a total of approximately 74 gallons, or 15.2%.

Table 2. Summary Data from Beta Test Example Two.

Control	Time (minutes)	Tails BPL (percent)	Plant Set Fatty Acid (gal/min)	Control Curves Fatty Acid (gal/min)	Total Fatty Acid Savings (gal)
Operator	0:00	1.803	1.831	1.368	
	15:00	2.350	1.714	1.318	
Control Curves	30:00	1.701	1.608	1.249	2.88
	45:00	2.480	1.673	1.250	4.79
	60:00	2.481	1.589	1.196	7.95
	75:00	2.561	1.581	1.160	11.24
	90:00	2.181	1.630	0.815	13.79
	105:00	1.943	1.377	0.873	20.13
	120:00	1.942	1.389	1.371	26.30
	135:00	5.133	1.407	1.045	32.19
	150:00	3.022	1.401	1.105	38.18
	165:00	2.147	1.444	1.104	43.52
	180:00	4.631	1.475	1.390	48.39
	195:00	4.632	1.410	1.338	54.24
	210:00	4.606	1.401	1.358	60.23
	225:00	1.686	1.465	1.035	65.25
	240:00	1.606	1.482	0.689	70.02
	270:00	2.266	1.538*	0.931	73.95
					73.95

* At this point, the flotation plant was actually running out of feed.

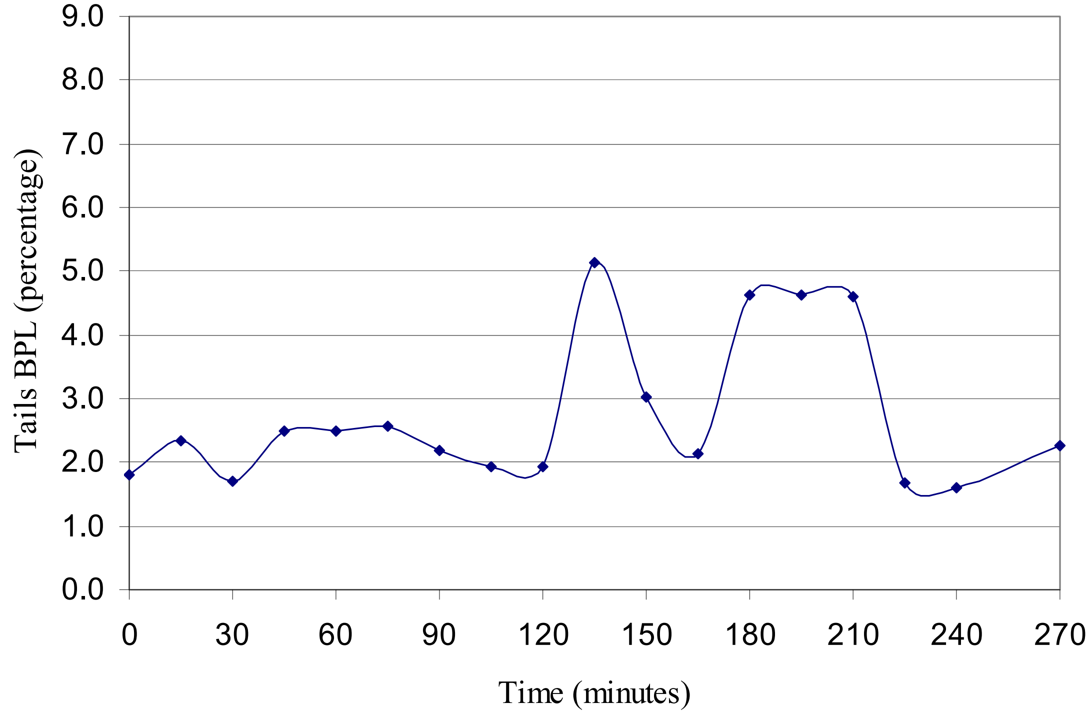

Figure 12. Tails BPL Versus Time.

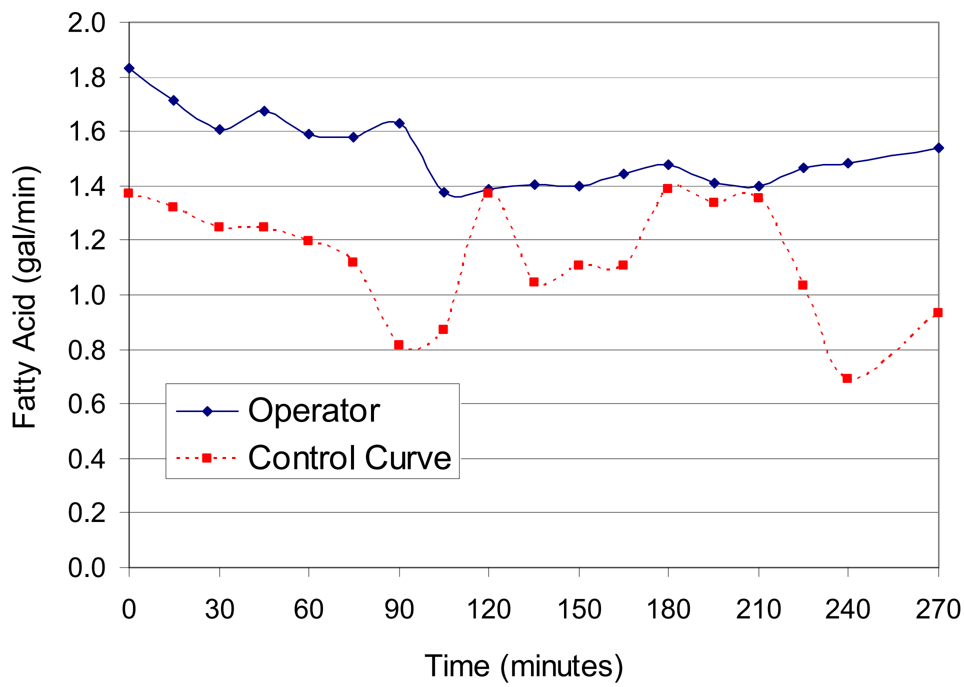

Figure 13. Fatty Acid Addition Versus Time.

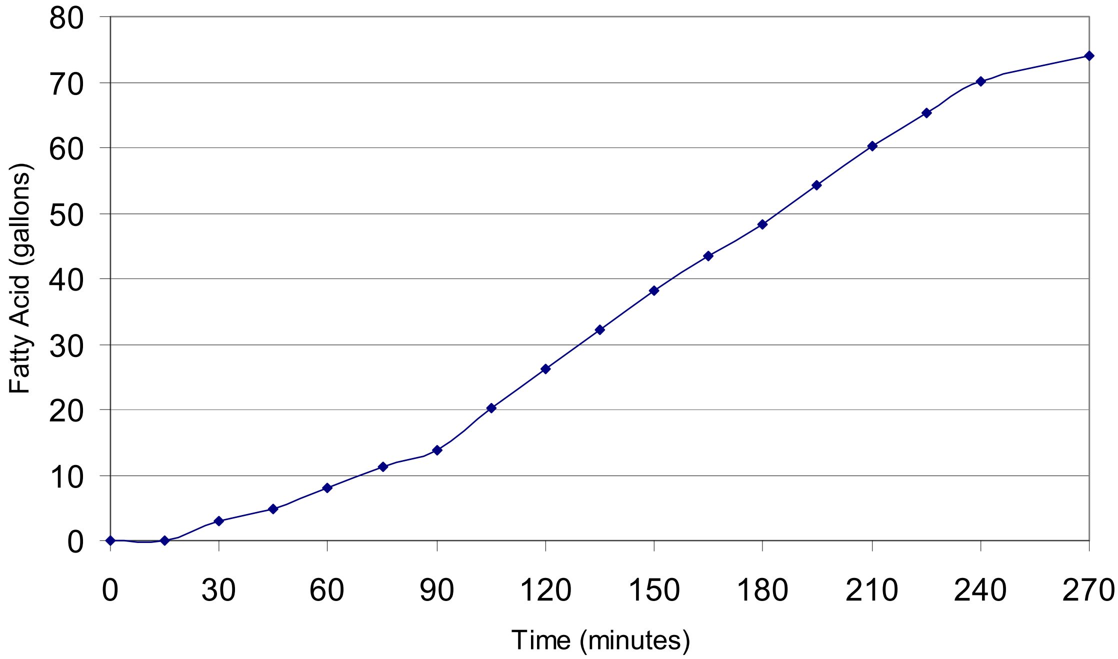

Figure 14. Total Savings in Fatty Acid Versus Time.

SUMMARY AND CONCLUSIONS

The recent decade has seen major advances in computer control systems. Despite the success of these systems in various industries, they are not well suited for the minerals processing industry for two major reasons. First, seldom to operating plants have on staff computer savvy individuals whose time can be dedicated exclusively to maintaining complex controllers. Second, most plants do not have the full array of instrumentation (data collection and analysis systems) required for implementing adaptive control systems. This report has detailed a very simple, yet effective approach, the Control Curve Approach, that can be effectively implemented in processing plants.

The Control Curve Approach relies on the reduction of generally readily available data to capture the operating strategies of effective plant operators. The fact that the approach is easily implemented via straightforward spreadsheet macros is an added benefit. The Control Curve Approach has been implemented and tested in PCS Phosphate's Swift Creek Mine facility. Results indicate that marked reductions in fatty acid usage are possible without any degradation in recovery. This report describes the details of the method's development, implementation, and performance.

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Phillips C, Karr CL, Walker G. 1996. Helicopter flight control with fuzzy logic and genetic algorithms. Engineering Applications Artificial Intelligence 9(2): 175-84.

ADDENDUM

2003 EXTENDED TESTING AT PCS SWIFT CREEK MINE

INTRODUCTION

BCD Technologies submitted a report in September 2002 to the Florida Institute of Phosphate Research (FIPR) describing work done toward the completion of the project "Controller Implementation to Improve Phosphate Recovery at PCS Phosphate's Swift Creek Mine." This report described a straightforward algorithm or approach for controlling phosphate processing plants. The approach described, termed the "Control Curves Approach," relies on a priori analysis of large amounts of operating data from the plant. The PCS Phosphate's Swift Creek Mine outside of Lake City, FL, was almost ideally suited for this task due to the existence of an MNR and associated data acquisition system. The data for the current study was collected over several months, then analyzed using spreadsheet macros written specifically for the task. This data analysis was straightforward and critical to the development of the Control Curves Approach. Upon completion of the data analysis portion of the development, the Control Curves Approach was easily encapsulated in a few spreadsheet commands implemented in the form of macros. This original report describes the Control Curves Approach, presents its implementation in a computer spreadsheet, and describes the results of implementing the control system at PCS Phosphate's Swift Creek Mine plant. Preliminary results presented in the original report indicated that the Control Curves Approach allowed for plant recoveries equitable to those achieved by human operators. In addition, the Control Curves Approach achieved its level of performance while utilizing far less conditioner than required by the human operators to achieve the same levels of performance.

The Control Curve Approach was field-tested at the PCS Phosphate Swift Creek Mine in the early fall of 2002. In this test series, based on feed BPL, the controller would decide on the amount of fatty acid required and the plant operator would lower the fatty acid level toward the recommended amount and operate for a brief period of time (typically an hour) to obtain several NMR readings on the circuit's performance. This process was repeated and the fatty acid feed rate would be lowered again, and data collected. These preliminary results showed that at the lower fatty acid levels the recovery remained at or above 90%. Tests were performed on different flotation circuits (Swift Creek has four rougher flotation circuits) to demonstrate the robust nature of the approach. When moving to test a different flotation circuit, the feed rate suggested by the controller for the original circuit were typically left unchanged as testing on a new circuit was being performed. These flow rates would be left unchanged for hours, thereby providing results over extended periods of time. Results for these periods were excellent.

Figure A-1 summarizes the system performance as achieved in the preliminary tests for an operating period of approximately one hour. Note from the curve that fatty acid addition usage was markedly lower when the Control Curve Approach was implemented. In fact, over the one-hour operational period, the Control Curve Approach was able to save almost 13 gallons of fatty acid. Extrapolating over an entire shift, or even over a month or longer, this is a dramatic economic saving to the company, without any loss in performance in recovery (perhaps even improved performance). These preliminary results indicate that the approach implemented has the potential to save PCS Phosphate tremendous expense they have incurred due to excessive fatty acid usage.

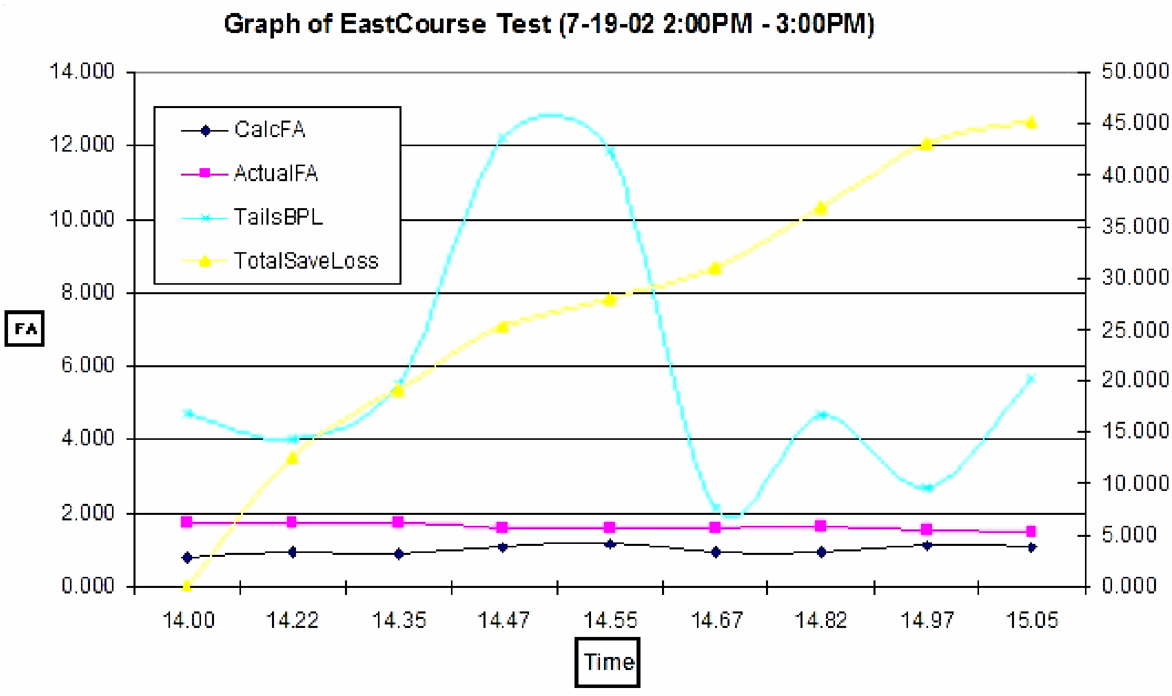

Figure A-1. Fatty Acid Addition and Tails BPL Versus Time.

Subsequent to the completion of the initial report describing the results of the Control Curves Approach for effectively manipulating phosphate processing, BCD Technologies has revisited PCS Phosphate's Swift Creek Mine to perform extended testing (Beta-testing) of the Control Curves Approach. This Addendum to the original report describes the results achieved during the Beta-testing.

TESTING PROCEDURE

The main objective of the Beta-testing conducted at the Swift Creek Mine during the week of August 11-15, 2003 was to run the Control Curves Approach for extended periods of time. Since the initial test results demonstrated that the control approach was robust enough to effectively manipulate a variety of rougher flotation circuits, the Beta-testing was focused on but two of the four rougher flotation circuits.

The Beta-test was conducted according to the following procedure. The controller was used to compute an amount of fatty acid required in the rougher flotation circuit. This value was implemented via a direct link to the automated system, thereby overriding the human operator who served simply as a safeguard against potential problems. The fatty acid was adjusted toward the recommended fatty acid level, and allowed to operate for a period of time to obtain several NMR readings on the circuit's performance. This process was repeated, the fatty acid feed rate was adjusted again, and data was collected. For example, let's say that the circuit was operating at 1.8 gallons per minute at the start of the test. The controller calculated that 1.2 gallons per minute was needed, so the controller lowered the feed rate to 1.6 gallons per minute. After about an hour of operating at this level, the fatty acid was lowered again to 1.4 gallons per minute and operated for an hour. The results showed that at the lower fatty acid levels the recovery remained at or above 90%. Tests were performed on two different flotation circuits to confirm the robust nature of the approach. When moving to test a different flotation circuit, the feed rate suggested by the controller for the original circuit was typically left unchanged as testing on a new circuit was being performed

RESULTS

The Control Curves Approach was run for extended periods according to the strategy presented above. The circuit was allowed to stabilize then the automated system was invoked and compared to the "normal operating procedures" generally invoked in the plant. This section describes the results of two specific runs that were part of the Beta test.

Example One

Table A-1 shows the values obtained from a four-hour run in the Swift Creek plant on August 11, 2003. The values presented in the table are time, tails BPL (to show that the circuit is performing acceptably as described by "grade"), the calculated fatty acid addition as computed using the Control Curves Approach, the operator-prescribed fatty acid addition, and the total savings in fatty acid (since the beginning of the run). These data are also presented in a different form in Figures A-2 and A-3 below.

In this example, the plant operator controlled the plant for the first hour, the Control Curves Approach was used for the second hour, the plant operator controlled the plant for the third hour, and the Control Curves Approach was again used for the fourth hour.

Note that during the first hour of operation, the tails BPL is varying considerably. There are numerous reasons this can occur, including the fact that the plant feed can come from different draglines, the operator can be attempting to maximize the throughput, etc. During the second hour of operation (Control Curves Approach), the tails BPL is much more stable and the system is using less fatty acid. During the third hour of operation, the operator has the tails BPL stabilized and is using only slightly more fatty acid than prescribed by the Control Curves Approach. During the final hour of operation, the Control Curves Approach is again using less fatty acid, but allows the tails BPL to rise. These results are consistent with the Control Curves Approach, which was implemented with the intent of minimizing fatty acid usage.

Table A-1. Summary Data from Beta Test.

Control	Time (minutes)	Tails BPL (percent)	Plant Set Fatty Acid (gal/min)	Control Curves Fatty Acid (gal/min)	Total Fatty Acid Savings (gal)
Operator	0:00	3.604	1.788	1.439	
	15:00	8.298	1.842	1.638	
	30:00	4.498	1.768	1.541	
	45:00	2.404	1.759	1.557	
Control Curves	60:00	3.859	1.628	1.232	
	75:00	4.594	1.576	0.923	
	90:00	4.296	1.581	1.198	
	105:00	4.768	1.601	1.542	9.00
Operator	120:00	7.449	1.811	1.648	
	135:00	7.513	1.833	1.733	
	150:00	4.806	1.784	1.632	
	165:00	6.069	1.888	1.542	
Control Curves	180:00	5.738	1.879	1.579	
	195:00	6.187	1.909	1.747	
	210:00	4.551	1.915	1.841	
	225:00	5.383	1.920	1.570	0.00
					9.00

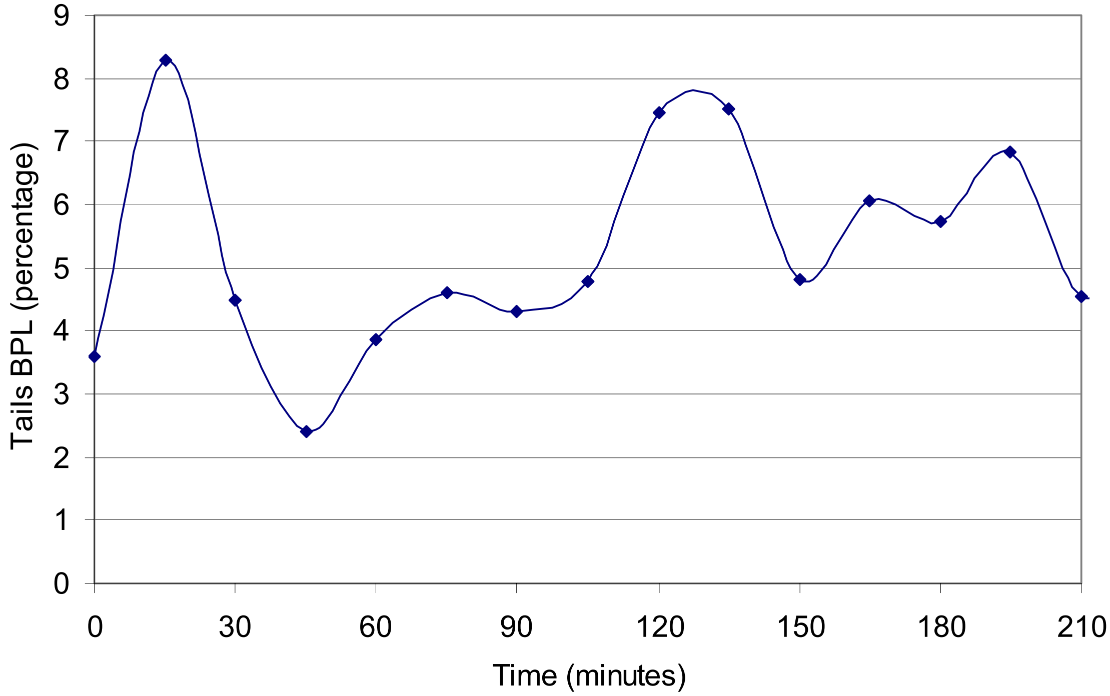

Figure A-2. Tails BPL Versus Time.

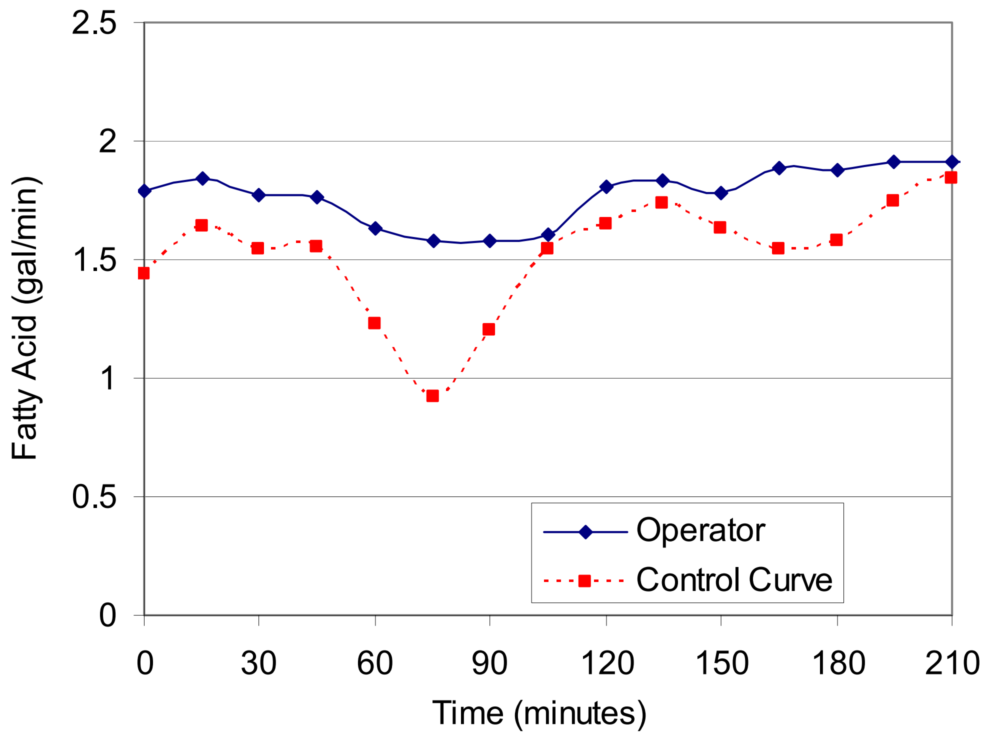

Figure A-3. Fatty Acid Addition Versus Time.

An advantage of the Control Curves Approach is that the operator has the ability to manipulate the extent to which the controller focuses attention on the fatty acid addition as opposed to the tails BPL. This fact is depicted in Figure A-4, which shows what the fatty acid addition would have been if alternative control curves had been used. In this figure, "Control Curve 1" shows the fatty acid addition prescribed by the system using the control curve actually employed during the test. The other curves represent fatty acid additions that would have been prescribed by the Control Curves Approach had alternative control curves (contained within the computer software) been utilized. Note that the control curve used is the most aggressive with regards to minimizing fatty acid usage. "Control Curve 4", on the other hand, is most aggressive with regard to manipulating the tails BPL. This feature of the software allows the plant operator to focus on various objectives.

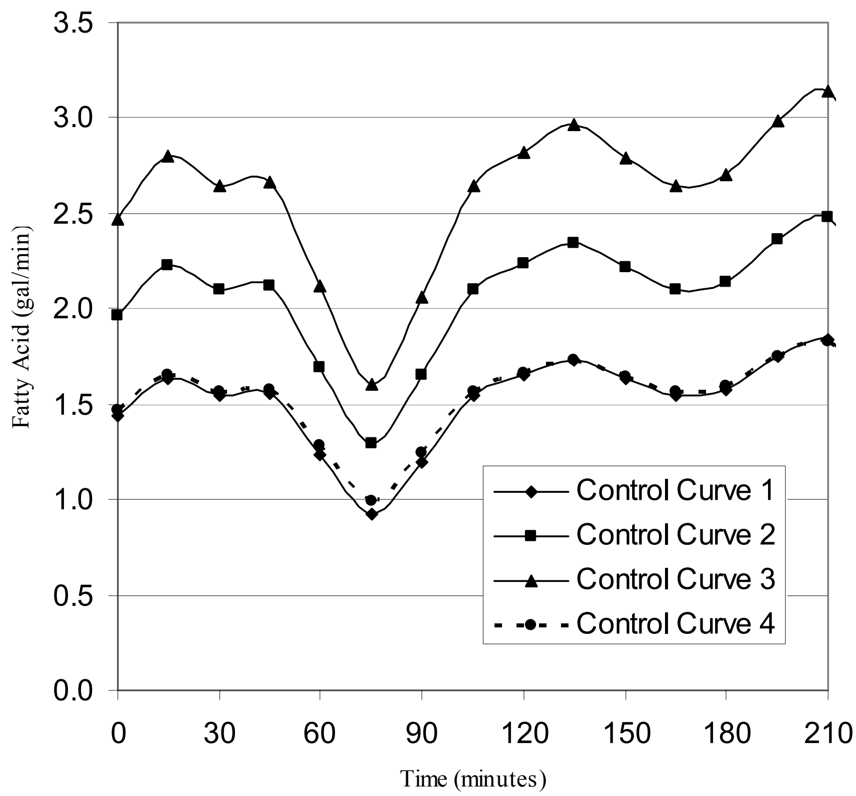

Figure A-4. Different Recommended Fatty Acid Additions from Various Control Curves.

This example demonstrates the fact that the Control Curves Approach can actually provide a savings in fatty acid. In addition, it brings to light the fact that different control curves can be employed to achieve varying objectives, e.g., reducing fatty acid addition versus decreasing tails BPL. This flexibility allows the operator to implement a control algorithm consistent with current goals.

Example Two

The second sample test was conducted differently from the first example presented previously. In this example, the operator initially gained control over the system. Then, the Control Curves Approach was implemented and allowed to manipulate the fatty acid addition for an extended period. Table A-2 shows the results of this effort. In this scenario, it should be clear that it is possible to run the system efficiently while using less fatty acid than typically thought. This data is shown graphically in Figures A-5 to A-7. Figure A-5 shows the value of the tails BPL as a function of time. Basically the purpose of this figure is to demonstrate that the plant is operating at an acceptable level of efficiency. Figure A-6 demonstrates that the Control Curves Approach consistently prescribes a reduced amount of fatty acid. Figure A-7 shows the savings in fatty acid that were achieved during the course of the four hour test--a total of approximately 74 gallons, or 15.2%.

Table A-2. Summary Data from Beta Test Example Two.

Control	Time (minutes)	Tails BPL (percent)	Plant Set Fatty Acid (gal/min)	Control Curves Fatty Acid (gal/min)	Total Fatty Acid Savings (gal)
Operator	0:00	1.803	1.831	1.368	
	15:00	2.350	1.714	1.318	
Control Curves	30:00	1.701	1.608	1.249	2.88
	45:00	2.480	1.673	1.250	4.79
	60:00	2.481	1.589	1.196	7.95
	75:00	2.561	1.581	1.160	11.24
	90:00	2.181	1.630	0.815	13.79
	105:00	1.943	1.377	0.873	20.13
	120:00	1.942	1.389	1.371	26.30
	135:00	5.133	1.407	1.045	32.19
	150:00	3.022	1.401	1.105	38.18
	165:00	2.147	1.444	1.104	43.52
	180:00	4.631	1.475	1.390	48.39
	195:00	4.632	1.410	1.338	54.24
	210:00	4.606	1.401	1.358	60.23
	225:00	1.686	1.465	1.035	65.25
	240:00	1.606	1.482	0.689	70.02
	270:00	2.266	1.538*	0.931	73.95
					73.95

* At this point, the flotation plant was actually running out of feed.

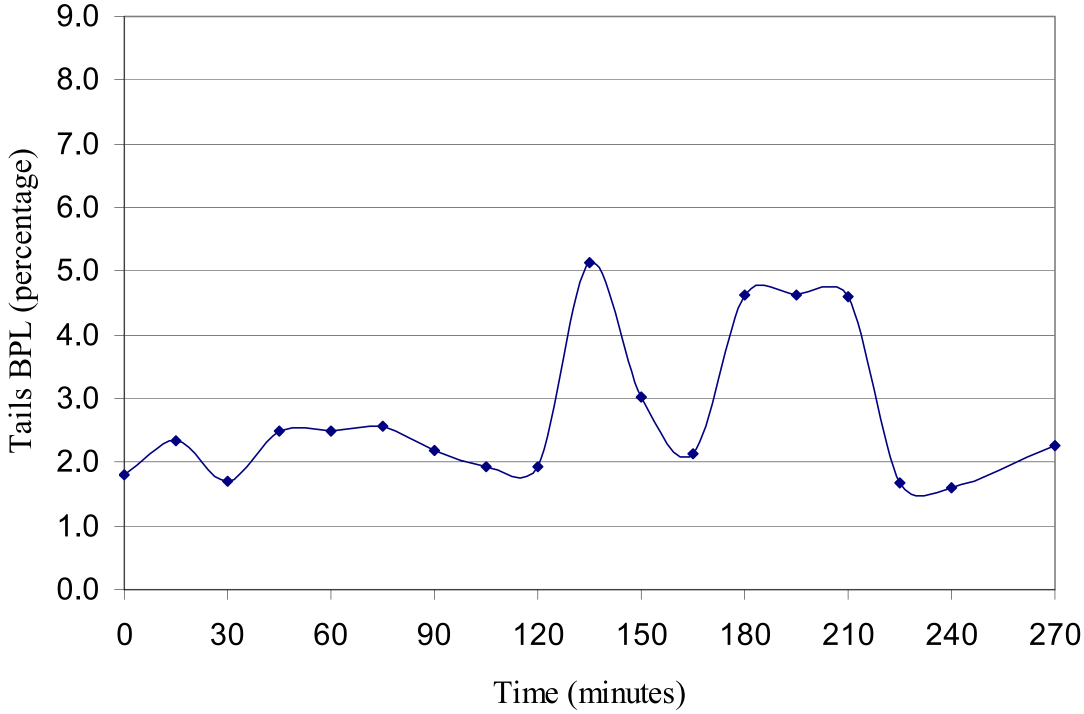

Figure A-5. Tails BPL Versus Time.

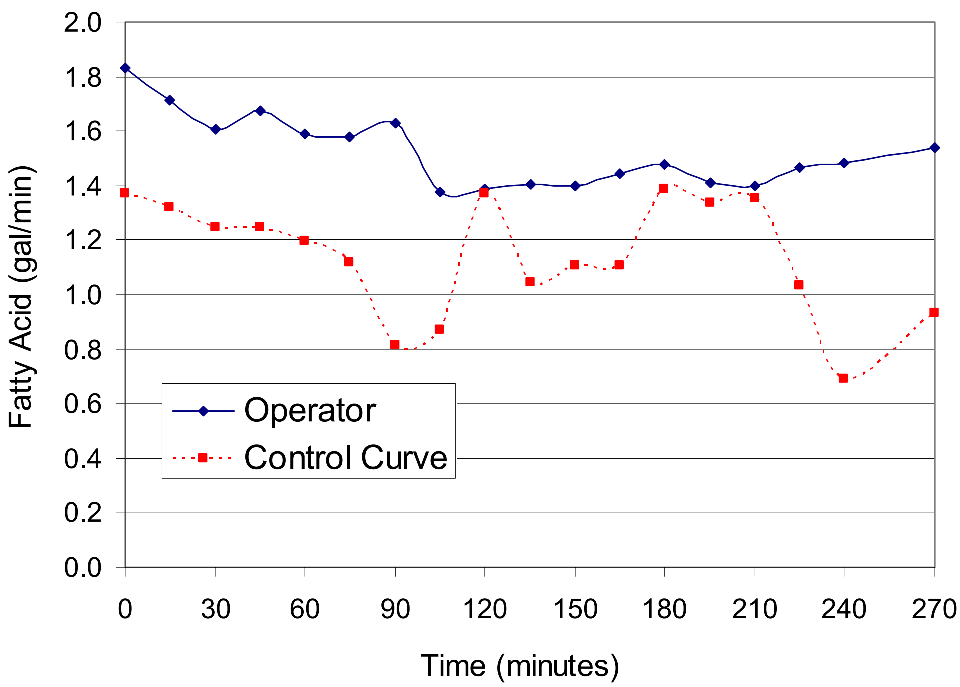

Figure A-6. Fatty Acid Addition Versus Time.

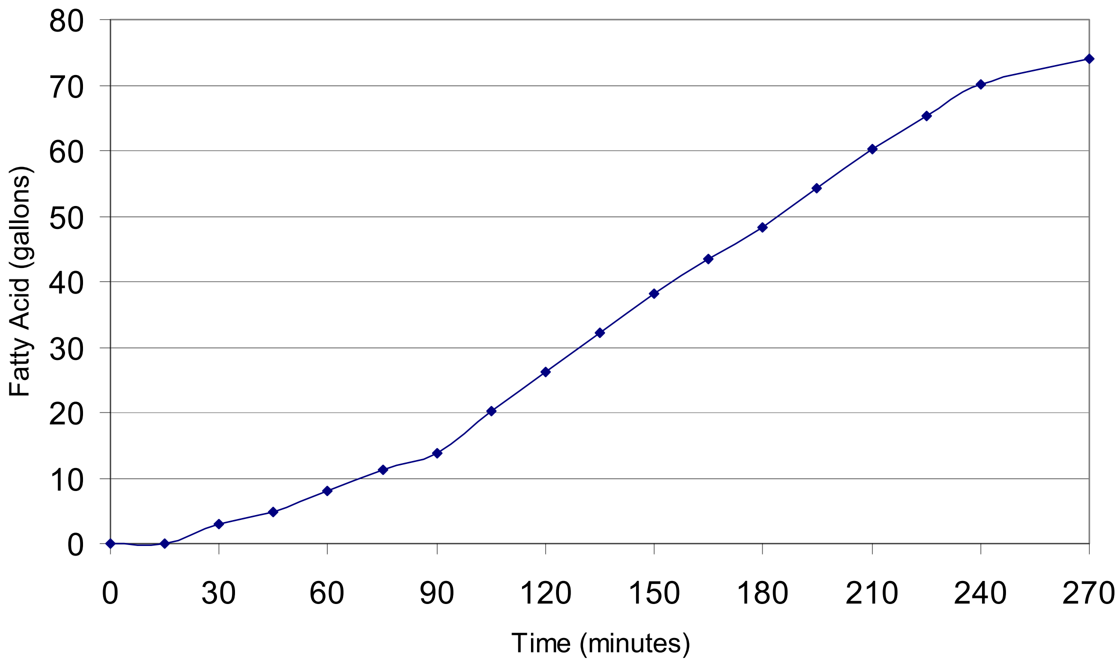

Figure A-7. Total Savings in Fatty Acid Versus Time.

SUMMARY AND CONCLUSIONS

The Control Curves Approach developed by BCD Technologies under the FIPR project entitled "Controller Implementation to Improve Phosphate Recovery at PCS Phosphate's Swift Creek Mine" was Beta tested during the week of August 11-15, 2003. This approach was initially described in a previous report. The objective of this addendum to the original report is to demonstrate that the system is effective for extended periods of time. Results presented herein demonstrate that the straightforward approach to controlling a phosphate processing plant is able to maintain a stable circuit while achieving acceptable performance levels using less fatty acid than typically used by human operators in the plant.