FINAL TECHNICAL REPORT
November 1, 2000 through December 31, 2001

Project Title:	EVALUATION OF NEW COAL SIZING TECHNOLOGIES TO IMPROVE PLANT PROFITABILITY
ICCI Project Number:	00-1/4.1A-1
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ABSTRACT

An improvement in the size separation performance for fine coal could potentially increase the overall quantity and quality of coal recovered from the fine coal cleaning circuits of Illinois coal preparation plants. Thus, the main objective of this study was to evaluate state of the art screening and classification technologies to improve fine coal sizing performance. The new technologies studied in this investigation include the Pansep screening technology, Krebs' new design gMax cyclone and the Cyclowash attachment with an industrial size cyclone. The Pansep screen's performance has been evaluated for 100 mesh particle size separation and compared with the performances of sieve bend and 15 inch cyclones operating in an Illinois coal preparation plant. The performances of 6-inch gMax cyclone, the Cyclowash attachment and also the Pansep screen have been evaluated for 325 mesh size separation and compared with the 6-inch cyclone of conventional design operating in an Illinois coal preparation plant.

The optimized Pansep screen performance is significantly better than the performance of 15-inch cyclone and sieve bend for classifying the minus 1 mm particle size slurry at 100 mesh. The undersize bypass was reduced from nearly 27% with 15-inch cyclone to nearly 2% with the Pansep screen. The undersize bypass of nearly 22% from the sieve bend was reduced to nearly 2% with the Pansep screen. Similarly, the optimized new design gMax cyclone performance obtained for near 325 mesh particle size classification is significantly better than the conventional cyclone design. The undersize and over size bypass amounts were reduced from nearly 32% to 12% and 3% to nil, respectively. Both undersize and oversize bypass amount were completely eliminated by the use of the Cyclowash. However, the injection of high amount elutriation water to minimize the undersize bypass increased the $d50_c$ separation size. The Pansep screening achieved a near perfect efficiency value of 98% to 99% for both 100 and 325 mesh size separation. A cost-benefit analysis conducted for one Illinois coal preparation plant suggests that the increased capital and operating cost of Pansep screening technology for 100 mesh size separation will be far offset by the additional revenue generated from preventing the fine coal loss due to the inefficiency at the 15 inch cyclone.

EXECUTIVE SUMMARY

The performance from many Illinois coal preparation plant could be improved by enhancing the performance from the fine coal cleaning circuit. The integration of advanced technologies for achieving high efficient cleaning and dewatering performance in the coal cleaning plants may be a sure way of improving the fine coal circuit performance. However, by simply improving the size classification efficiency also a significant additional benefit can be realized from the existing cleaning technologies being used in the coal preparation plants.

Thus, the main objective of this study was to evaluate state of the art screening and classification technologies to improve fine coal sizing performance. The new technologies studied in this investigation include the Pansep screening technology, Krebs' new design gMax cyclone and the Cyclowash attachment with an industrial size cyclone. The Pansep screen's performance has been evaluated for 100 mesh particle size separation and compared with the performances of sieve bend and 15 inch cyclones operating in an Illinois coal preparation plant. The performances of 6-inch gMax cyclone with and without the Cyclowash attachment and the Pansep screen have been evaluated for 325 mesh size separation and compared with the 6-inch cyclone of conventional design operating in an Illinois coal preparation plant.

Statistically designed experimental programs were pursued for quick identification of the key operating parameters and the subsequent optimization of these operating parameters to achieve target classification performances. In addition, the statistical data analysis also intended to study the operating parameter effects on the various classification performance parameters. This experimental study was conducted at the Illinois Coal Development Park utilizing a Pansep screen having 0.5 m^2 of screening surface area, 15 cm (6 inch) diameter g-Max classifying cyclone and a KH-3 Cyclowash. A 2^{5-2} fractional factorial design and two 3-factor Box Behnken designs were conducted for optimizing the Pansep screen performance for 100 mesh and 325 mesh size separations. Similarly a 3-factor Box Behnken design was conducted to optimize the gMax cyclone performance, whereas 5-factor Plackett-Burman design and 4-factor Box Behnken design experimental programs were conducted for identifying and optimizing the key process parameters for the Cyclowash.

The optimized Pansep screen performance was found to be significantly better than the performance of 15-inch cyclone and sieve bend for classifying the minus 1 mm particle size slurry at 100 mesh. The undersize bypass was reduced from nearly 27% with 15-inch cyclone to nearly 2% with the Pansep screen. The corresponding improvement in the sharpness of size separation is indicated by an improvement in the corrected *selectivity index* and *imperfection* values from 0.51 and 0.33 to 0.23 and 0.64, respectively. An overall particle size separation efficiency of 57% obtained from the 15-inch Cyclone and 44% obtained from the VariSieve were improved to 98% by the Pansep screen. The improved size separation efficiency was achieved mainly due to the decreased undersize bypass to the overflow stream in comparison to the VariSieve, whereas both decreased

undersize bypass and sharper separation caused the efficiency enhancement in comparison to the 15-inch cyclone.

The optimized new design gMax cyclone performance obtained for 325-mesh classification was significantly better than the conventional cyclone design used in the plants. The undersize and oversize bypass amounts were reduced from nearly 27% to 12% and 3% to nil respectively. Both undersize and oversize bypass were completely eliminated by the use of the Cyclowash, while improving the imperfection and selectivity index values from 0.34 and 0.56, respectively, to 0.22 and 0.64, respectively. However, the injection of high amount elutriation water to improve the Cyclowash performance also increased the separation size. The Pansep screen achieved excellent overall size separation efficiency of nearly 99% due to negligible amount of bypass materials and sharper separations.

An economic analysis was conducted to estimate the potential plant profitability achievable due to the integration of Pansep technology in place of 15 inch Cyclones to an Illinois coal preparation plant treating nearly 370 tph of coal in its fine circuit. Due to the inefficiency at the classifying Cyclone, an estimated 59 tph of minus 100 mesh size coal having an ash content of nearly 40% is directly lost to the plant thickener. This fine coal loss can be potentially reduced to 3 tph by using Pansep screens. The resulting increased coal recovery of 56 tph may generate additional annual revenue of $ 6.7 million dollars considering nearly 7000 working hours per year and a selling price of $1.05/mBtu. More than $ 6 million dollars of additional revenue will far offset the increased annual capital and operating cost of $136, 000 incurred due to the installation of Pansep screens in the plant in place of the existing 15-inch cyclones. By replacing the Sieve bends and VariSieves used for desliming the spiral product by the Pansep screens will potentially decrease the ash content of the screen overflow clean coal product. This will not only improve the overall quality of the clean coal from the fine coal circuit, but also aid the dewatering process due the reduced ultrafine ash material content of the dewatering feed slurry.

The 6-inch diameter Cyclone banks used to deslime the minus 100-mesh particle size fraction in the coal preparation plant produce very poor classification performance. Nearly 54% of the undersize materials present in the feed are misplaced to the Cyclone underflow and nearly 18% of the oversize material is lost to the overflow. The presence of extremely high amount of misplaced ultrafine materials having a very high ash content is highly detrimental to the conventional flotation process. In addition, the commercialization of the enhanced gravity separators to effectively clean the 28 x 325 mesh size fraction will warrant a significantly more efficient 325-mesh size classification. The Pansep screen providing nearly 99% overall size separation efficiency may prove to be the technology to solve the ultrafine classification problem. However, further investigation is recommended to improve the throughput capacity of the Pansep screen while maintaining high efficient size classification.

OBJECTIVES

The overall goal of this project was to demonstrate two state of the art coal screening and classification technologies to improve the quality and quantity of the fine clean coal product and thus, increase plant profitability. The technologies evaluated for achieving 100 mesh and 325 mesh size separations include Pansep screening technologies, Krebs' new design gMax cyclone and the Cyclowash. The specific project objectives were:

1. To evaluate the newly developed Pansep Screening Technology for achieving fine (100 mesh) and ultrafine (325 mesh) particle size separations. The target misplacements for the 100 mesh and 325 mesh particle size separations were less than 5% and 10%, respectively.

2. To evaluate the Krebs' new design 6 inch diameter gMax cyclone and Cyclowash units for their desliming performances at 325 mesh. The target misplacement was less than 10%.

3. To compare the performance obtained from the traditional screening and classification units operating in an Illinois coal preparation plant with that of Pansep screen and Cyclowash system.

4. To conduct an economic analysis for commercializing the new coal sizing technologies and estimating the resulting plant profitability.

INTRODUCTION AND BACKGROUND

The physical separation processes utilized in coal preparation plants to obtain a desired Btu recovery and pyrite rejection are effective only for a specified particle size range. Beyond the optimum size range the separation efficiency of the processes are affected drastically. For example, the conventional flotation process achieves an effective separation in the 60 x 325 mesh particle size range. The presence of finer clays (minus 325 mesh) affects the separation process and results in a decreased product quality due to the hydraulic entrainment problem. Many preparation plant operators complain that the performance from their flotation banks suffer due to the presence of undesirable ultrafine clay particles in their flotation feed even after undergoing a desliming classification process. In addition, presence of coal particles of in-appropriate size also causes a significant loss of clean coal to the reject stream. For example, the spiral banks in a coal preparation plant achieve an efficient separation in the 16 x 100 mesh particle size range. Most of the finer (minus100 mesh) materials report to the fine coal product stream and is ultimately rejected to the thickener as the sieve-bend underflow, thus causing a loss of recoverable fine clean coal.

To improve the performance from fine coal circuit, several enhanced gravity separators have been developed over the past several years including Falcon Concentrator, which was developed at SIU with the research funds received from Illinois Department of Commerce and Community Affairs (IDCCA) and Illinois Clean Coal Institute (ICCI). A low cost and high capacity enhanced gravity separator like Falcon Concentrator could be used very effectively to reject the coal pyrites while achieving a high Btu recovery thus lowering the sulfur dioxide (SO_2) emission potential of the high sulfur Illinois coal. However, Falcon concentrator is known to perform effectively only over a particle size range of 16 x 325 mesh and its performance deteriorates sharply beyond this particle size range. Thus, a precise 325-mesh particle size-cut is a pre-requisite for a successful commercialization of Falcon concentrator as well as other enhanced gravity concentrators.

The fine coal sizing technologies used in the existing coal preparation plants include vibratory screens, sieve bends and classifying cyclones.

Vibratory Screens:

High frequency vibratory screens allow maximum repeated incidence of particles to the screening surfaces increasing the probability of undersize materials to pass through the screen opening. Vertical vibration is induced either by the rotation of a mechanical reciprocating device applied to the casing or by electrical devices operating directly on the screen, as shown in Figure 1 (a) of Appendix-I. Although extensively used in the coal industry, the high frequency vibratory screens have numerous drawbacks, which includes inefficiency, short life of screen mesh due to shaking and the continuous feeding into one part of the screen, high maintenance cost, excessive noise and a large foot print.

Sieve Bend:

The most beneficial feature provided by the sieve bend is its hydraulic capacity per foot area. Since the fine particle streams in a coal preparation plants are associated with a rather large water content resulting in excessively high volumetric flow rates, sieve bends find a wide application in the fine coal cleaning circuit of a coal preparation plant. Krebs VariSieve^{TM}, shown in Figure 1 (c) of Appendix-I is an improved sieve bend design. However, a significant amount of the fine ash material typically still reports along with the sieve bend overflow, thus lowering the product quality. Screen blinding, lack of open area due to build-up of material, high maintenance cost and mesh wear commonly result in sub-par performance for the sieve-bends (Buisman and Reyneke, 2000)

Classifying Cyclones:

In the conventional cyclone design, shown in Figure 1 (b) of Appendix-I, the fluid enters the cylindrical section of the cyclone tangentially and an upward vortex is created at the center of the cyclone due to the swirling motion of the fluid. The solid particles in the fluid are subjected to a centrifugal field by which the larger particles are moved to the cyclone wall at a faster rate than the smaller particles. This difference in the lateral position of the smaller and larger particles inside the cyclone causes the former to report to the overflow with the vortex and the latter to report to the underflow.

Classifying cyclones of varying sizes are used for fine and ultrafine classification in Illinois coal preparation plants. The minus1mm feed coal stream is traditionally classified by using 15 inch diameter cyclones to prepare a 1mm x 100 mesh fraction to be treated by spirals and a minus100 mesh fraction as a feed to the desliming (6 inch diameter) cyclones. The desliming cyclones provide a nominally 100 x 325 mesh coal fraction to be treated in the flotation bank and a high ash overflow (minus325 mesh) to be discarded into the thickener. Classifying cyclones are very popular in the coal industry due to their high capacity. However, the cyclones suffer from a significant amount of particle bypass (as high as 20 to 30%) to the underflow. The inefficiency at the 15 inch cyclone dilutes the spiral feed with unwanted minus100 mesh coal fines, which are ultimately rejected as the sieve bend underflow, causing loss of valuable clean coal. The ultrafine particle by-pass at the desliming cyclones produces a flotation feed consisting of a significant amount of unwanted ultrafine ash material, which is detrimental to the conventional flotation performance.

This study aimed at demonstrating two new technologies as suitable alternatives to the currently used relatively inferior fine coal sizing technologies in the Illinois coal preparation plants. The fine coal cleaning performances resulting from the improved sizing has been calculated and the resulting plant profitability evaluated. The results of these technical and economic evaluations are the subject matter of this report. For the convenience of the readers, a list of the original tasks proposed is provided as follows:

Task 1: Sample Collection and Characterization: Three different samples from various process streams of American Coal Company will be collected to be used in this study. The processing streams will include:

1. 15-inch classifying cyclone feed (nominally –16 mesh) slurry.
2. Spiral clean coal product (sieve bend feed slurry)
3. 6-inch desliming cyclone feed (nominally –100 mesh) slurry.

The samples will be collected in 55 gallon barrels and transferred to the pilot-plant research facility at SIU. Before starting the experimental program the samples will be homogenized in a large tank to collect representative samples for size-by-size weight, ash, sulfur and Btu analysis.

Task 2: Pansep Screen Evaluation:

To conduct a scientific study and optimize the screening performance of newly developed Pansep Screening technology for both fine (100 mesh) and ultrafine (325 mesh) size cuts, this research task has been subdivided into following six sub tasks.

Task 2.1: Procurement and Installation of the Equipment at SIUC

During the initial two months of the project initiation a continuously operating single deck Mini-Pansep Screen will be procured and installed in the pilot-plant research facility of SIU. The technical personnel from the Dewar Inc. will provide help during the installation and initial run of the machine to train the research staff at SIU. A recirculation feed arrangement equipped with a pump and sump will be made to run the screening device in a continuous mode.

Task 2.2: Exploratory Test Program to Determine the Key Process Parameters

Pansep Screening technology has a variety of process (both design and operating) parameters that needs to be studied to determine the key parameters. After conducting few preliminary experiments, some of the parameters will be selected and 12 experiments will be conducted using a Placket & Burmen experimental design to statistically evaluate the key process parameters according to the order of their importance. Based on this study the key process parameters will be identified to further optimize the performance in task 2.3

Task 2.3: Performance Optimization using the Key Process Parameters for an efficient 100-mesh particle size cut.

Upon identification of the key process parameters a 3-factor level Box-Behnken experimental design will be pursued to further optimize the process parameters. Depending on whether 3 or 4 key parameters are selected, 17 or 29 experiments will be conducted using a standard combination of operating parameter values to generate the required data for statistical analysis. The response performance variables that will be studied in this test program may include Cut size (d_{50}), particle by-pass (α) and the imperfection (I). The target screening performance will be the lowest I and α and highest SI at a desired d_{50} value of 100 mesh. An optimum experimental region will be determined to achieve this target screening performance. Five additional experiments will be conducted to validate the model predictions and also check the repeatability of the device.

Task 2.4: Performance Optimization using the Key Process Parameters for an Efficient 325-mesh particle size cut.

The same exercise as described in Sub task 2.3 will be conducted to achieve a d_{50} value of 325 mesh with the lowest possible I and α values and highest possible SI values.

Task 2.5: Evaluation of the Existing Plant Screening Performance for both 100 mesh and 325 mesh Screening

To evaluate the performance of the competing unit operations operating in the American Coal's Galatia preparation plant, five gallon bucket samples will be collected around the 15 inch classifying cyclone, sieve bend and the 6 inch desliming cyclones. Size-by-size analysis of each sample will be conducted in the laboratory to generate size partition curve, $d_{50,}$ I, SI, and α values for the existing unit operations in the plant.

Task 2.6: Comparison of Performance

A performance comparison will be conducted to show the improvement that can be potentially resulted by replacing Pansep screening unit in place of 15 inch classifying cyclones, sieve bends and the 6 inch desliming classifying cyclones.

Task 3: New Design Cyclowash System

Task 3.1: Installation of a 6 inch Cyclone Circuit

Between the 6th and 7th project months a 6-inch classifying cyclone with the new design Cyclowash attachment supplied by the Kreb's Engineers will be installed in the pilot-plant research facility of SIU. The personnel from the Krebs will provide technical help during the installation and set-up the of the cyclone circuit. A recirculation feed arrangement equipped with a pump and sump will be made to run the system in a continuous mode.

Task 3.2: Optimization of the New Design Cyclowash attached to a 6 inch Cyclone

The Cylcowash optimization study will examine the effects of the key process parameters. Based on several exploratory tests and the results obtained from an on-going Cyclowash study the key process parameters will be identified. A 3-factor level Box-Behnken experimental design will be pursued to further optimize the process parameters. Depending on whether 3 or 4 key parameters are selected, 17 or 29 experiments will be conducted using a standard combination of operating parameter values to generate the required data for statistical analysis. The response performance variables that will be studied in this test program may include Cut size (d_{50}), particle by-pass (α) and the imperfection (I). The target classification performance will be the lowest I and α at a desired d_{50} value of 325 mesh. An optimum experimental region will be determined to achieve this target screening performance. Five additional experiments will be conducted to validate the model predictions and also check the repeatability of the device.

Task 3.3: Comparison of Results

The Cyclowash results will be compared with that obtained from the Pansep screen for the 325-mesh size cut and the plant desliming cyclones.

Task 4: Economic Analysis

An economic analysis will be conducted in direct consultation with the Dewar Inc.'s personnel and the American coal company personnel to determine the screening capital and operating cost both for 100 mesh and 325-mesh size cuts. Similar exercise will be conducted in direct consultation with the Krebs Engineers to evaluate classification capital and operating costs for the classification with the new design Cyclowash unit. These costs will be compared with that of the competing conventional technologies used in the plants. An overall plant profitability calculation will be conducted using these analysis and the incremental improvement in the plant performance that will be resulted from the commercialization of these new coal sizing devices in a typical Illinois coal preparation plant

Task 5: Report Preparation:

Monthly progress reports and a Mid-year technical and management report will be submitted throughout the duration of this project as per the guidelines given by Illinois Clean Coal Institute. After the completion of the project, a final report containing a summary of all test results and data analyses will be submitted. The final report will also provide recommendations and proposed outline of the Phase II plant demonstration study.

EXPERIMENTAL

Sample Collection

Three different samples from various process streams of an Illinois coal preparation plant was were collected for this study. These processing streams included:

1. 15-inch classifying cyclone feed (nominally minus16 mesh) slurry.
2. Spiral clean coal product (sieve bend feed slurry)
3. 6-inch desliming cyclone feed (nominally minus100 mesh) slurry.

A total of 50 fifty-five gallon barrels of samples were collected and transferred to the pilot-plant research facility at SIU. Before starting the experimental program the samples were homogenized in a large tank to collect representative samples for size-by-size weight, ash, sulfur and Btu analysis.

Pansep Screen Evaluation: Experimental Layout and Procedure

A novel fine particle screening technology known as the Pansep Screen has been recently developed and commercialized by the Particle Separation Systems in South Africa. Figure 1 shows the schematic of a Pansep Screen. The Pansep principle incorporates a system of separate non-flexing screen cloths each tensioned within its own frame (Brown et al., 2000 and Ryeneke, 2000). The series of segmented pans are mechanically linked together to form a “big chain”, which is rotated by a drive-motor at a desirable speed. The essential advantage of the Pansep screen is that the screen cloth could effectively be of any type appropriate to the duty required, without consideration of a need for flexibility or resilience to fatigue. The screen selection is therefore governed by the separation characteristics required, including open area ratio, accuracy and shape of apertures. A consequent benefit was also the facility to use the return pans for screening operations, by using the reverse side after an intermediate wash. This effectively doubles the capacity for a given screen size.

As shown in Figure 1, the feed slurry is introduced to the moving screen panels through a uniform feed distributor. The screening of the undersize material is assisted by the spray

Figure 1. The schematic of a Pansep Screen recently developed and commercialized in South Africa. (Buisman and Ryeneke, 2000)

maintained to avoid a build-up of a thick layer of solid material on the screen surface, which is detrimental to the screening efficiency. Undersize particles are drained and washed through the mesh openings whereas oversized particles are discharged into an oversize chute. After being self-rinsed, the clean mesh panels rotate around the sprocket and are again introduced to the incoming slurry on the return run. This way, the feed slurry throughput capacity of the Pansep screen is doubled for the same footprint.

The bulk slurry samples collected from the 15 inch cyclone feed stream and the spiral product-sieve bend feed streams were treated with the Pansep screen to evaluate its screening efficiency at 100 mesh particle size. On an experimental day, several barrels of the slurry sample are mixed the feed sump, shown in the experimental layout of Figure 2 and Figure 2 of Appendix-I. The pump flow is adjusted to set the desired feed flow rate using a magnetic slurry flow meter while recirculating the feed slurry and a feed sample taken. Prior to turning the two-way valve to stop recirculating and start feeding the Pansep screen, the spray water is turned on and the Pansep screen is set to motion at the desired speed. Overflow and underflow samples are collected after allowing the screen to run for a few minutes to achieve a steady state condition. Upon collecting all three samples from the feed, overflow and underflow streams, the two-way feed valve is rotated to stop feeding and start recirculating the coal slurry followed by the stoppage of the screen motion and the water spray. The same process is continued as described to conduct the subsequent tests. To be able to conduct a number of tests required for the completion of the test program with the limited amount of sample, the overflow and underflow streams of the Pansep screen are collected together in a settling tank as shown in Figures 2 and 2 of Appendix-I.

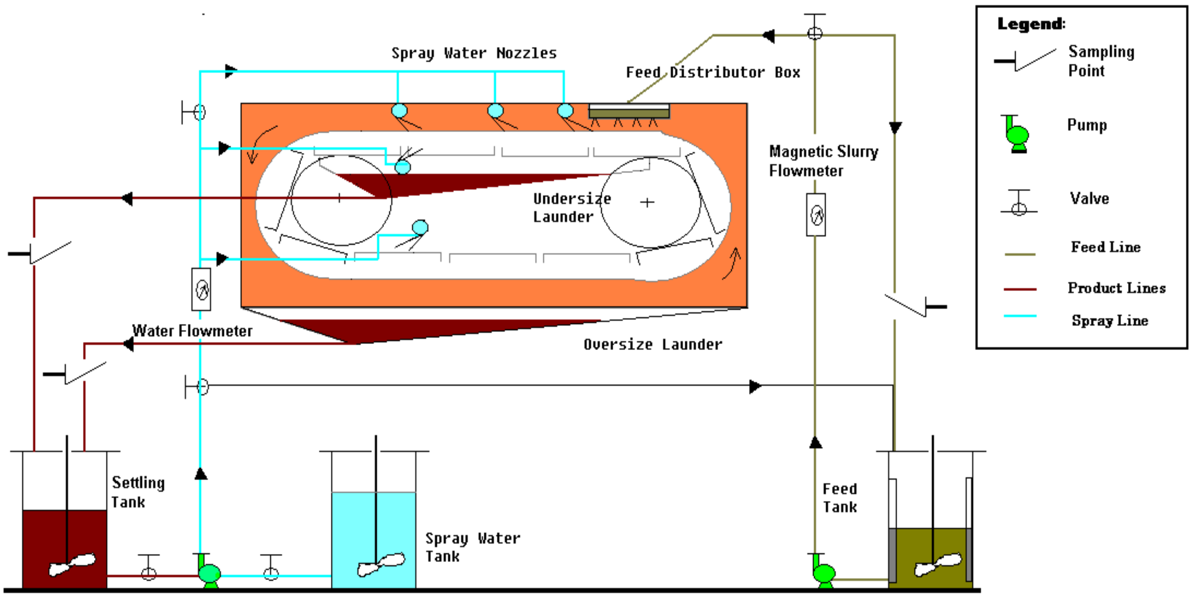

Figure 2: A schematic of the experimental layout utilized to evaluate the Pansep Screen in the Illinois coal development park.

The diluted coal slurry in the settling tank is left to settle for a few days to allow a complete settling of all solid particles before a calculated amount of supernatant clear water is siphoned out to adjust the solid content to the original level. The second pump in the circuit, which is used as a spray water pump while running the experiments, is utilized to pump the coal slurry from the settling tank to the feed tank to get started with one more test series.

New Design gMax Cyclone: Experimental Layout and Procedure:

Classifying cyclones have been traditionally used in coal preparation plants to achieve fine particle size separation. Krebs Engineers Inc., which is one of the largest manufacturers of the classifying cyclones internationally, has conducted a significant amount of research over the years to improve the fine classification performances of the cyclones. The gMax cyclone, shown in Figure 3 of Appendix-I, is one of their re-engineered new cyclone design developed to produce finer and sharper cyclone separations at relatively high throughput capacity (Olson, 2001).

The gMax includes improved apex and conical section design as well as feed inlet and cylindrical section design to minimize the turbulence in the feed chamber while maximizing tangential velocity in the critical separating zone of the cyclone. The increased tangential velocity results in a finer separation for a cyclone of the same diameter and reduced misplaced fines in the underflow. The re-engineered inlet head area and a longer vortex finder reduces the turbulence in the feed chamber and thus, reduces the misplacement of the coarser material to the overflow of the cyclone.

The feed slurry sample for the 6-inch desliming cyclone collected from the plant was treated with the 6-inch diameter gMax cyclone to evaluate its efficiency for classifying at 325-mesh particle size. On an experimental day, several barrels of the slurry sample are mixed in the gMax feed sump, shown in the experimental layout in Figure 3. The feed slurry is well mixed with a stirrer and a recirculation stream as shown in the layout. The vortex finder and apex of desired sizes are used in the gMax for each test. By gradually shutting the recirculation valve to a certain level a desired amount of feed slurry or in other words a desired amount of feed slurry pressure is maintained. The feed, overflow and underflow samples are collected for each test for subsequent size analyses to determine the classification performance of the gMax cyclone.

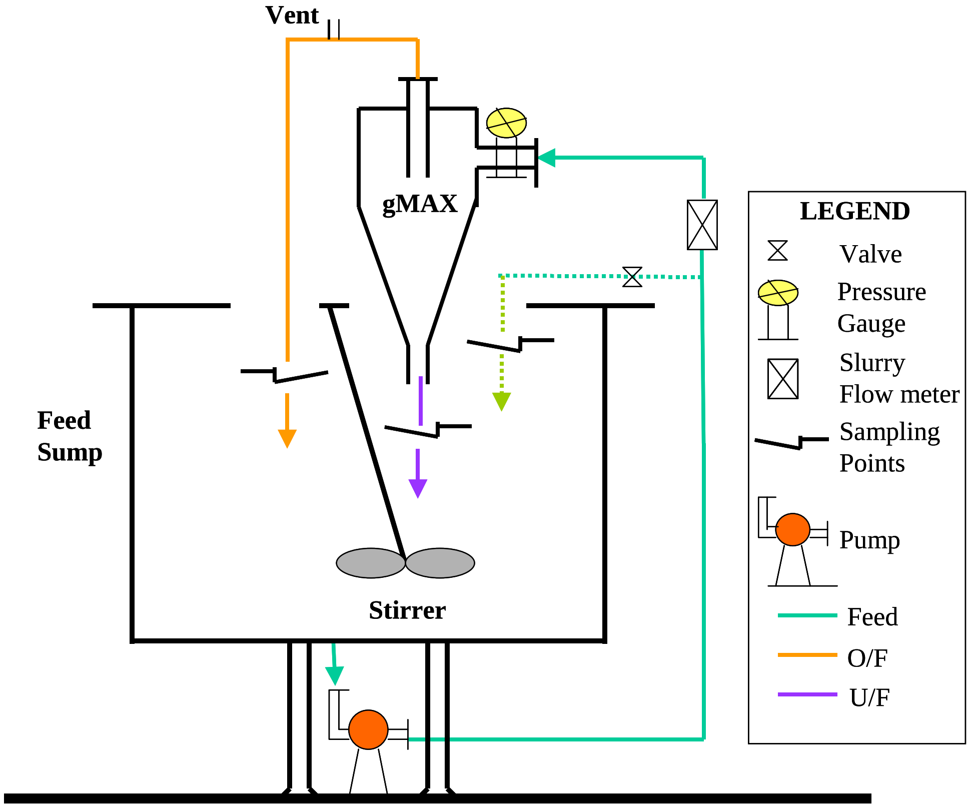

Figure 3: A schematic diagram of the experimental layout utilized for the gMax cyclone evaluation in the Illinois coal development park.

Cyclowash Test Layout and Procedure:

The Krebs Cyclowash is an elutriation device, which significantly improves the desliming performance of the classifying cyclone of traditional design. The additional features that the Cyclowash system provides to a classifying cyclone are the water injection arrangement above the apex and the truncated cone as shown in Figure 4 of Appendix-I. The truncated cone is placed slightly above the apex (spigot) of the cyclone dividing the cyclone into two sections. Primary classification of the feed materials takes place in the upper section of the cyclone. Upon entering the bottom section, the classified materials are subjected to a tangential injection of elutriation water. As a result, the fine particles entrained in the underflow pulp are displaced and discharged with the cyclone overflow. Thus, the Cyclowash attachment reduces the misplacement of fines in the classifying cyclone underflow. An analogy can be made with the froth washing of flotation columns, where the feed pulp water reporting to the froth zone is substituted by the wash water added minimizing the amount of entrained ultrafine ash material being recovered to the product launder.

The feed slurry sample for the 6-inch desliming cyclone collected from the plant was treated with the gMax cyclone attached with a Krebs Cycolwash to evaluate the performance improvement achievable using the Cyclowash. On an experimental day, several barrels of the slurry sample are mixed in the feed sump, shown in the experimental layout in Figure 8. The feed slurry is well mixed with a stirrer and a recirculation stream as shown in the layout. The vortex finder, apex and truncated cone of desired sizes are used for each test. By gradually shutting the recirculation valve to a certain level a desired amount of feed slurry is introduced to the cyclone or in other words a desired amount of feed slurry pressure is maintained. The feed, overflow and underflow samples are collected for each test for subsequent size analyses to determine the classification performance of the gMax cyclone.

Since there is an external source of elutriation water that is constantly added for the Cyclowash operation, the overflow and underflow slurry cannot be just mixed together to form the original feed slurry. The combined underflow and overflow slurry is left in a settling tank for a few days to facilitate a complete settling of all solid particles. A calculated amount of supernatant water is removed from the settling tank to maintain the original solid content of the feed slurry before pumping to the feed tank as shown in Figure 4.

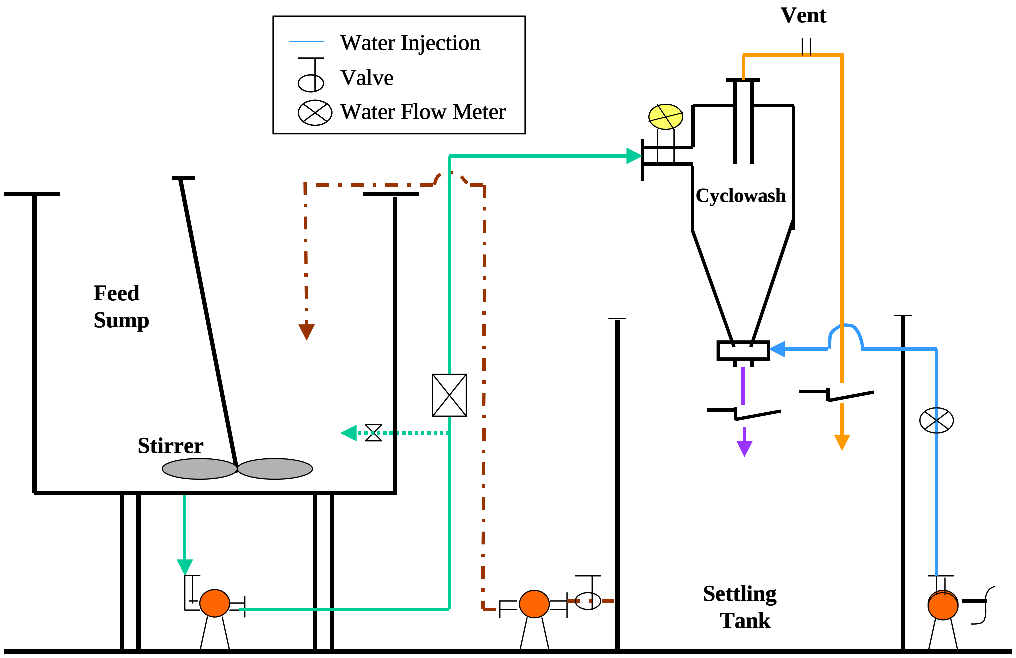

Figure 4: Experimental layout utilized for the evaluation of Cyclowash

RESULTS AND DISCUSSIONS

Task 1: Sample Collection and Characterization

Detailed size-by-size characterizations were conducted on the coal slurry samples collected from the three different process streams of an Illinois coal preparation plant. The analyses included the determination of the distribution of weight, ash, total sulfur and calorific values for the constituent size fractions resulting from the wet-sieving of the individual samples. As the Table 1 indicates the feed slurry to the 15 inch classifying cyclone in the plant contains nearly 19% of the + 1mm particles The minus325 mesh particle size fraction has a very high ash content of over 62%, which justifies the need for 6 inch diameter desliming cyclones for the 15 inch cyclone overflow.

The high proportion of nearly 46% of minus325 particle size fraction in the spiral product-sieve bend feed slurry is indicative of a significantly high bypass of ultrafine materials to the underflow of the 15-inch cyclones. The low heating value of 9524 lb/Btu of spiral product is due to the presence of relatively high ash minus325 mesh particle size fractions, which are mostly removed at the sieve bend. The feed materials of 6-inch cyclones, which are actually the overflow materials from the 15-inch cyclones, have a higher concentration of high ash and higher sulfur content materials.

Table 1: The size-by-size distribution of weight, ash, sulfur and heating value contents of coal samples collected from all three process streams used in this study.

15 inch Classifying Cyclone Feed

Size Fraction		Weight	Ash Content	Total Sulfur	Heating Value	SO2
(mesh)	(micron)	(%)	(%)	(%)	(Btu/lb)	(lbs/mbtu)
+16	+1000	20.81	8.02	1.12	13939	1.61
16 x 28	1000 x 595	13.05	5.25	1.03	14027	1.47
28 x 65	595 x 210	20.37	5.18	0.951	13933	1.37
65 x 100	210 x 149	5.96	6.34	0.989	14385	1.38
100 x 200	149 x 74	8.18	12.34	1.12	12662	1.77
200 x 325	74 x 44	4.45	34.24	1.7	9237	3.68
-325	-44	27.18	62.14	1.100	3333	6.60
TOTAL		**100.00**	**23.21**	**1.09**	**10779.34**	**2.99**

Spiral Product - Sieve bend Feed

Size Fraction		Weight	Ash Content	Total Sulfur	Heating Value	SO2
(mesh)	(micron)	(%)	(%)	(%)	(Btu/lb)	(lbs/mbtu)
+16	+1000	10.29	21.53	2.1	10965	3.90
16 x 28	1000 x 595	34.59	25.61	4.0	10986	7.26
28 x 65	595 x 210	28.29	27.44	4.0	11057	7.18
65 x 100	210 x 149	11.39	18.52	4.1	11620	6.97
100 x 200	149 x 74	1.59	16.07	3.1	12198	5.02
200 x 325	74 x 44	2.89	17.08	2.8	12376	4.44
-325	-44	10.99	47.31	1.6	7304	4.24
TOTAL		**100.00**	**26.89**	**3.48**	**10730.72**	**6.41**

6 inch Desliming Cyclone Feed

Size Fraction		Weight	Ash Content	Total Sulfur	Heating Value	SO2
(mesh)	(micron)	(%)	(%)	(%)	(Btu/lb)	(lbs/mbtu)
'+100	+149	1.50	8.92	2.12	13339	3.18
100 x 200	149 x 74	6.73	12.10	2.17	12684	3.42
200 x 325	74 x 44	7.00	28.25	2.88	10376	5.55
325 x 400	44 x 37	3.95	28.30	3.63	10693	6.79
400 x 500	37 x 25	8.20	28.81	3.62	10338	7.00
-500	-25	72.62	56.17	1.60	5978	5.35
TOTAL		**100.00**	**47.20**	**1.98**	**7391.09**	**5.40**

Task 2: Pansep Screen Evaluation

Evaluation for 100 mesh size separation

Exploratory Test Program

Since the Pansep technology was a completely new screening technology having an entirely different screening mechanism, several series of exploratory tests were conducted to obtain a better understanding of the Pansep screening mechanism, the relevant operating parameters and the suitable operating range of the parameter values. The broad conclusions drawn from the exploratory test results presented in Tables 1, 2 and 3 of Appendix-II are as follows:

- Rotational speed of the screen does not appear to play any important role at lower feed rate of 98 lpm (nearly 25 gpm) of feed volumetric rate; however at higher feed rate of 210 lpm (of nearly (55 gpm), the screening efficiency improved at higher rotational speed. By increasing the screen speed, the individual mesh pans start moving faster under the feed distributor and hence material loading per pan is decreased. This allows a thinner material bed in each mesh pan facilitating a better stratification of material on the screen surface, which results in the better screening efficiency.

- Change in angle of spray appeared to aid the stratification of the material bed and thus, results in better screening efficiency to a certain degree. The performance was improved by spraying at an angle of 22.5^o instead of vertically downwards; however, the *undersize bypass* appeared to increase at an increased spray angle of 45^o apparently due to relatively poor draining of the screen mesh pans with an angular spray.

Fractional Factorial Design

Several series of exploratory tests conducted in this test program established the possible range of operating parameter values that could be used for subsequent studies. However, before proceeding with the optimization test program, it was desired to identify the key operating parameters having significant effects on the performance of the Pansep screens. A series of 8 tests were conducted by varying all five-process parameters as a part of a fractional factorial design to select only the key operating parameters. The response, i.e., the performance parameters selected included the selectivity index (SI), imperfection (I) and the ultrafine bypass to the oversize. The corrected d_{50} and d_{95} values were also evaluated for each test as shown in Table 4 of Appendix-II.

Sizes by size analyses were conducted on each feed, overflow and underflow samples produced to generate the partition curves for each test. The selectivity index and imperfection values were calculated using the corrected partition coefficients and ultrafine bypass value was obtained from the uncorrected partition curves. The statistical analysis of the performance data revealed the operating parameters having significant effect on individual performances as listed in Table 4. As shown, feed flow rate, feed solids content, water spray angle and the rotational speed of the mesh panels were found to be having significant effect on the three performances studied. The water spray rate tested in the range of 50 to 100 lpm was not found to have significant effect on any of the performance parameters studied.

Although, the feed solids content was found to be a key operating parameter, it was desired not to vary the feed solids content in the subsequent test program since this optimization test program was being conducted for a specific coal preparation plant from where the samples were collected. A feed solids content of nearly 13% was maintained throughout the subsequent test program to be consistent with the plant feed solids content of the 100 x 0 stream. Thus, the key parameters selected to be further investigated in the optimization test program included feed flow rate, screen rotational speed and the water spray angle.

Optimization Test Program

Upon the identification of the key operating parameters, a more comprehensive Box-Behnken experimental design program was conducted to obtain a better understanding of the Pansep screening process and develop empirical models for individual performance parameters. The operating parameter values for the key parameters and the resulting performances for each test have been summarized in Table 5 of Appendix-II. As some of the results indicates excellent imperfection value of 0.26 and selectivity index value of 0.61 were achieved while maintaining the undersize bypass to the Pansep overflow below 3% for achieving a d50c size of nearly 100 mesh.

Table 4: A list of operating parameters having significant effects on individual screen performance parameters.

Affected Performance Parameters	Key Operating Parameters
Imperfection	Feed flow rate, Screen rotational speed and Spray angle
Selectivity Index	Screen rotational speed
Undersize Bypass	Feed flow rate and Feed solids content

The empirical model equations developed for *Imperfection (I)*, *Selectivity Index (SI)* and the *Undersize Bypass* to the overflow of the Pansep screen as a function of the key process parameters are presented in the following paragraph. The model equations consist of only those key operating parameter main effects and interaction effects, which were found to be statistically significant at an α (significance level) value of 0.05 or 5%. As shown, all main factors were found significant for predicting *imperfection* and *selectivity index*, whereas *undersize bypass* was found to be a function of screen rotational speed and spray angle.

$$I = 0.28 + 0.0008*A - 0.0138*B - 0.0014*C - 3.11E\text{-}06*A^2 + 9.286E - 05*A*B \qquad [1]$$

$$SI = 0.57 - 0.0008*A + 0.029*B + 0.00052*C + 1.84E\text{-}06*A^2 - 0.00378*B^2 \qquad [2]$$

$$\text{Log (Undersize By-pass)} = 0.50 + 0.0705*B + 0.0079*C \qquad [3]$$

Where, A = Feed Rate; B= Rotational Speed; C= Spray Angle

The only parameter interaction that was found significant for any of the performance parameters was feed rate-rotational speed. This interaction effect in other words means that for different feed flow rate, the optimum screen speed rate is different, which finding is very consistent with the experimental observation.

The perturbation plots shown in Figure 8 illustrate the degree of importance of each key operating parameter for individual performance parameters. As shown, volumetric feed rate and water spray angle have the maximum effect on the *imperfection* value, whereas the screen rotational speed has a minimal effect. Similarly for the *selective index* response, feed flow rate is the most important operating parameter followed by rotational speed and spray angle. On the other hand, for the *undersize bypass* to the Pansep overflow, feed flow rate has a minimal effect. The water spray angle and screen rotational speed have greater effect on the *undersize bypass*.

Using the empirical model equations, appropriate sets of experimental conditions were identified to achieve target separation performances as shown in Figure 5 of Appendix-I. As indicated in Table 5, the observed values are fairly close to the predicted ones. The predicted versus the observed screening performances shown in Figure 6 of Appendix-I, further validates the empirical models, which can be utilized to obtain any target performances.

Table 5: The comparison of the Pansep performances obtained from the model validation tests

Performance	Predicted	Observed
Imperfection	0.29	0.33
Selectivity Index	0.58	0.53
Undersize Bypass	6.1 %	6.4 %

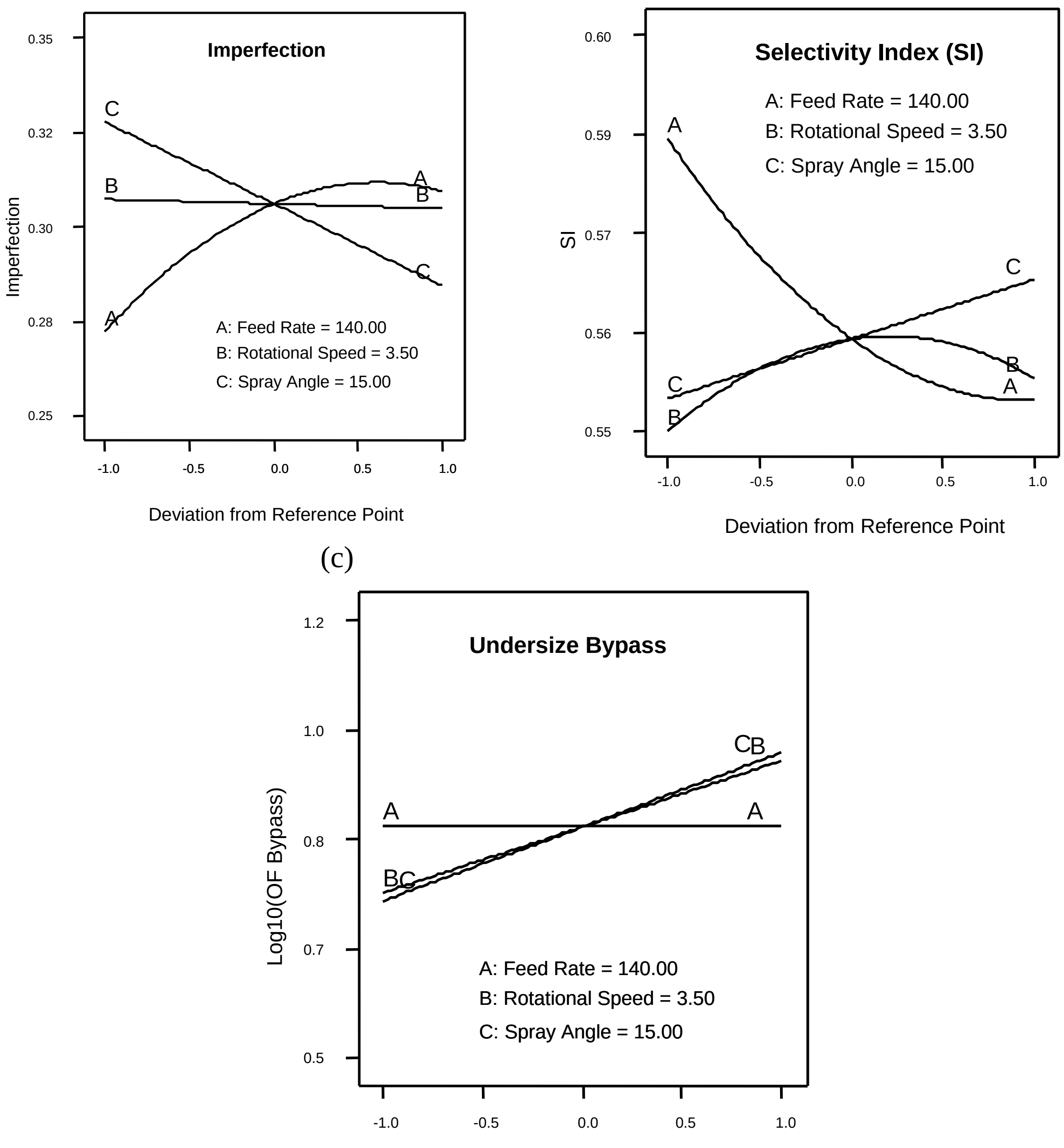
(a)
(b)
(c)

Figure 8: Perturbation plots for the three response variables (performance parameters) evaluated in this investigation. The medium values of the operating parameters are shown in the legend.

Pansep Evaluation for 325-mesh size separation

Exploratory Test Program: Special mesh panels were imported from South Africa for achieving 325 mesh size separation using the Pansep technology. A series of exploratory tests were conducted to investigate the hydraulic capacity and the need for adjusting the spray angle. Previously, for the 100 mesh size separation, the spray angle was varied over a range of 0 to 30^o; however it was found that the increasing spray angle had a negative impact on the overall efficiency of screening. During this exploratory test series very little difference in performance was observed over 15^o to 45^o. Thus, it was desired to maintain the spray angle constant for the optimization test program. As the results in the Tables 6 and 7 of the Appendix II indicate, the d50c size for all tests were above the desired 45-micron (325 mesh) probably due to the high feed volumetric rates.

Optimization Test Program: An optimization test program was conducted using the Box-Behnken experimental design. A total of seventeen tests were conducted by varying three key factors i.e., feed volumetric flow rate, feed solids content and the screen speed. The performance parameters evaluated included oversize (os) recovery to the screen overflow, undersize (us) recovery to the screen underflow, overall efficiency and the $d50_c$ separation size. As shown in the perturbation plots in Figure 11, feed solids content had the maximum effect on all the performance parameters evaluated, whereas the volumetric flow rate had a minimal effect. This may indicate the high hydraulic capacity of the Pansep screen, which is very important for fine coal screening. The $d50_c$ separation size increases with both feed solids content and increasing screen velocity. As shown, near perfect efficiency, oversize recovery to the overflow stream and undersize recovery to the underflow stream of 1.0 were achieved using the Pansep screen, which indicates the high efficient screening achievable even in the ultrafine size range.

Evaluation of Existing Technologies

The conventional fine coal sizing technologies that are used in the Illinois coal preparation plants typically include 15 inch classifying cyclone for raw coal classification at 100 mesh, 6 inch classifying cyclone for raw coal classification at 325 mesh and sieve bends (or vary-sieves) for spiral clean coal product at nearly 100 mesh.

15 inch Classifying Cyclone:

The entire fine coal feed slurry (nearly 350 tph) of the preparation plant under investigation is classified at 100 mesh using a bank of 15 inch classifying cyclones to separately clean the minus100 mesh and the plus100 mesh particle size fractions using different processing technologies. Although a $d50_c$ size of nearly the desired 100 mesh (149 micron) is achieved, the classification efficiency obtained from the traditional design plant cyclone is not satisfactory, as shown in Table 2. The cyclone underflow, which is supposed contain mostly the plus100 mesh particle size fraction, actually contains nearly 24% of minus100 mesh particle size material. A simple analysis indicates that this misplacement occurs due to high *imperfection* value of 0.57 and an *undersize* *particle bypass* of 29% as shown in Table 2 and Figure 5. On the other hand, the overflow has a very minimal amount of plus 100 mesh particle size fraction due to a very negligible *oversize bypass* to the cyclone overflow.

Sieve bend:

Several traditional design sieve bends and relatively new Krebs VariSieves are used in the plant to remove the minus100 mesh high ash material fraction and also to partially dewater the spiral product. Size by size analyses were performed on the VariSieve feed, overflow and underflow to evaluate the screening performance achieved at the VariSieve. As presented in Table 3 and Figure 6, the VariSieve also exhibit a significant amount of *undersize bypass* (of nearly 38 %) possibly due to the availability of limited screening surface area due to solid material build-up. The d50$_c$ cut size may also be relatively large for the same reason.

Table 2: The 15-inch cyclone performance

15 inch Classifying Cyclone

Size Fraction		Weight (%)		
(mesh)	(micron)	Feed	Underflow	Overflow
+16	+1000	20.81	28.10	1.31
16 x 28	1000 x 595	13.05	16.70	3.27
28 x 65	595 x 210	20.37	26.03	5.25
65 x 100	210 x 149	5.96	7.51	1.81
100 x 200	149 x 74	8.18	7.95	8.79
200 x 325	74 x 44	4.45	3.52	6.93
-325	-44	27.18	10.20	72.63
TOTAL		100.00	100.00	100.00
Oversize Bypass			1.71%	
Undersize Bypass			27.3	
Imperfection (corrected)			0.65	
Selectivity Index (corrected)			0.28	
d50c (corrected)			72	
d95c (corrected)			300	

Table 3: The plant sieve bend performance

Spiral Product - Sieve bend

Size Fraction		Weight (%)		
(mesh)	(micron)	Feed	Overflow	Underflow
+16	+1000	8.8	0.1	10.3
16 x 28	1000 x 595	29.8	1.2	34.6
28 x 65	595 x 210	25.4	8.1	28.3
65 x 100	210 x 149	11.4	11.4	11.4
100 x 200	149 x 74	6.3	34.6	1.6
200 x 325	74 x 44	3.4	6.2	2.9
-325	-44	14.9	38.3	11.0
TOTAL		100.00	100.00	100.00
Oversize Bypass			0.20%	
Undersize Bypass (% weight)			21.5	
Imperfection (corrected)			0.15	
Selectivity Index (corrected)			0.75	
d50c (corrected)			138	
d95c (corrected)			375	

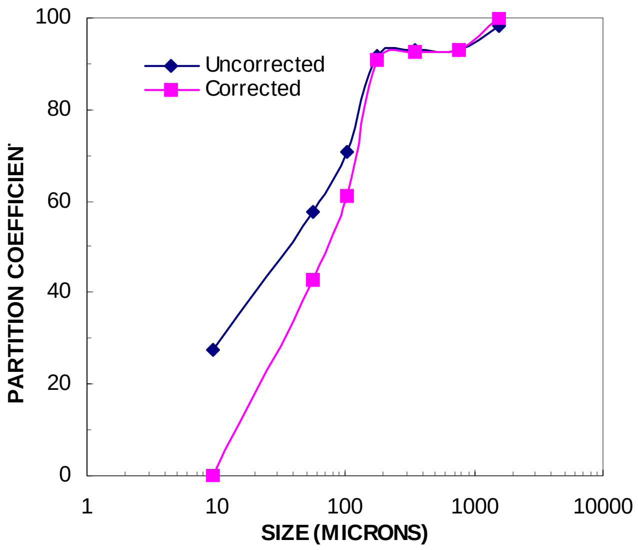

Figure 5: Partition curves for the 15-inch cyclone

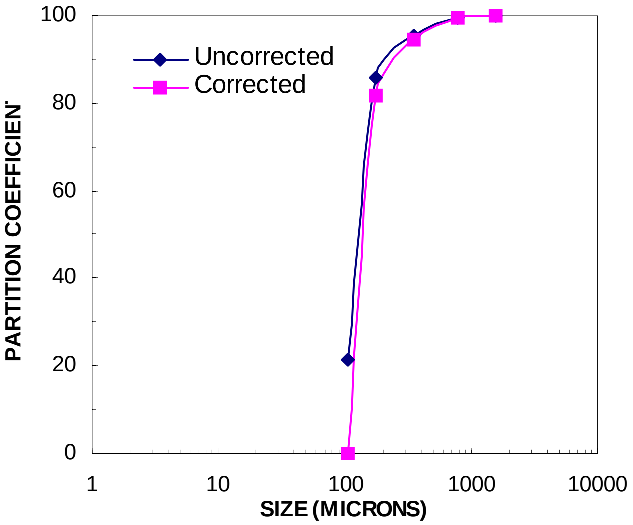

Figure 6: Partition curves for the plant sieve bend

Table 4: The 6-inch cyclone performance

6 inch Desliming Cyclone				
Size Fraction		Weight (%)		
(mesh)	(micron)	Feed	Underflow	Overflow
'+100	+149	1.50	2.50	0.10
100 x 200	149 x 74	6.73	9.93	2.23
200 x 325	74 x 44	7.00	8.89	4.33
325 x 400	44 x 37	3.96	2.17	6.47
400 x 500	37 x 25	8.20	6.42	10.70
-500	-25	72.62	70.10	76.16
TOTAL		100.00	100.00	100.00
Oversize Bypass (% weight)			2.7	
Undersize Bypass (% weight)			32	
Imperfection (corrected)			0.3	
Selectivity Index (corrected)			0.6	
d50c (corrected)			50	
d95c (corrected)			155	

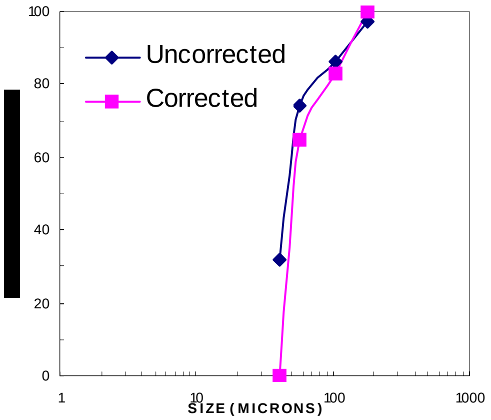

Figure 7: The partition curve for the 6-inch cyclone

New Task (not described in the original proposal): New Design gMax Cyclone Evaluation

Exploratory Test Program

Based on a discussion with the research group at Krebs Engineers the different sizes of vortex finder and apex that were selected to be used in the subsequent optimization study included 1.5, 2.0 and 2.5 inch for vortex finder and 0.75, 1.0 and 1.25 inch for apex. A suitable feed pressure range of 14.5 to 23.5 psi, i.e., 100 to 162 kPa was established for all possible combination of various sizes of vortex finder and apex. As some selected test data presented in Table 6 indicates, increasing feed pressure provided finer cut size and decreasing oversize bypass to the overflow. However, the difference between the classification performance between 138 kPa (20 psi) and 173 kPa (25 psi) is quite insignificant.

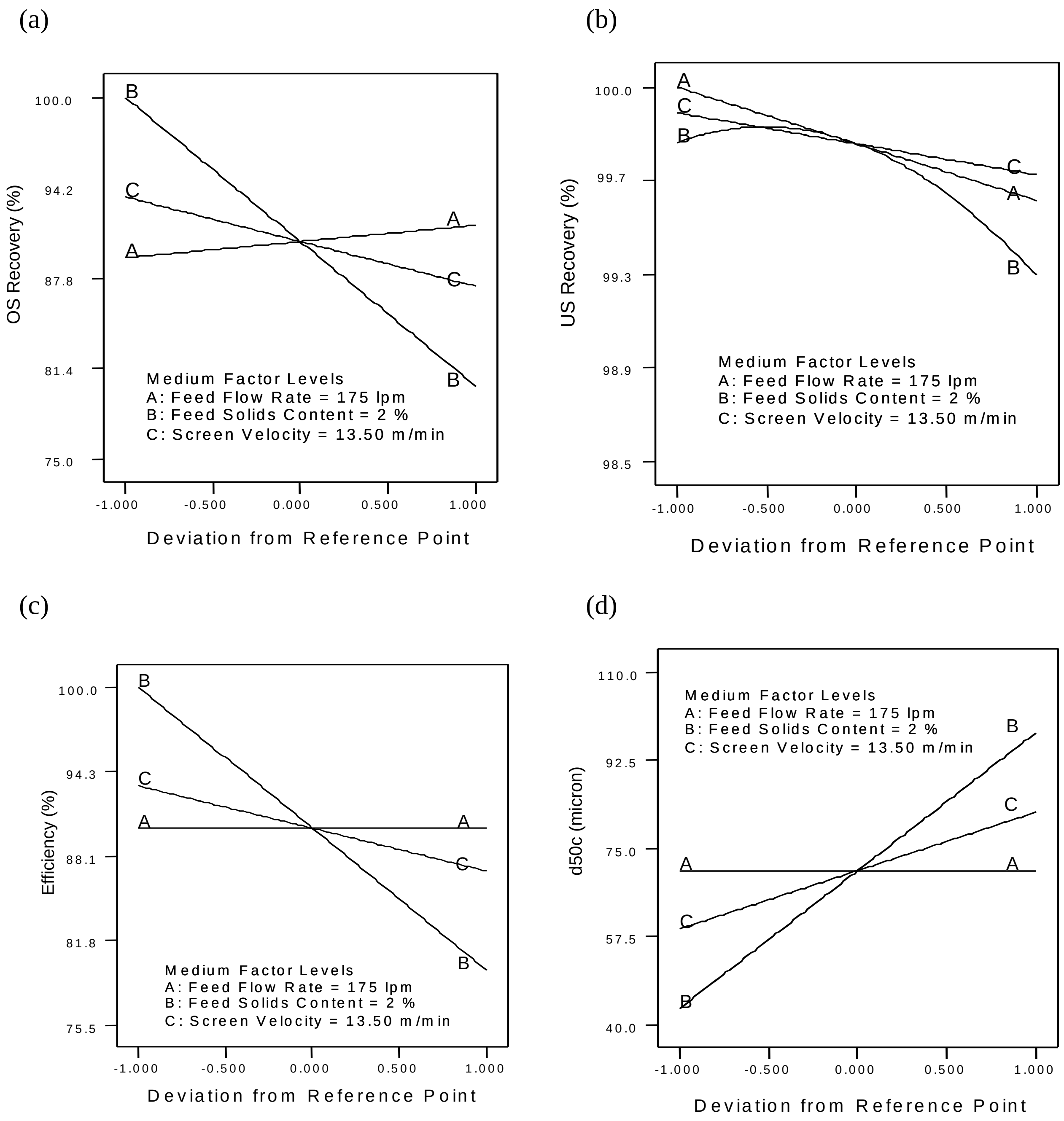

Figure 11. Perturbation plots for four important response variables (performance parameters evaluated for the 325 mesh separation using the Pansep screen.

Table 6: Operating parameter values and test results for a selected exploratory tests conducted for gMax Cyclone. VF: 1.5 inch; Apex: 1.0 inch.

Operating Parameter Values		Results				
Test #	Feed Pressure (kPa)	Undersize Bypass (% weight)	Oversize Bypass (% weight)	d50c (micron)	Imperfection	Selectivity Index
1	173	30.15	0	28	0.44	0.42
2	138	26.05	0.3	31	0.40	0.43
3	104	25.54	5.13	36	0.33	0.48

<u>Optimization Test Program</u>

Since gMax cyclone design is very recently developed at Krebs' Engineers, a comprehensive Box-Behnken test program was conducted to optimize the classification performance of this new design cyclone. A series of 17 experiments was designed by varying the vortex finder diameter, apex diameter and the feed pressure at three levels each as shown in Table 8 of Appendix-II. Overflow, underflow and feed samples from each test were analyzed for individual particle size contents to evaluate the classification performance values for each test as presented in Table 8 of Appendix-II. The different performance parameters evaluated included $d50_c$, $d95_c$, *imperfection, selectivity index, oversize bypass* and *undersize bypass*. Suitable empirical models were developed, as shown below, to describe a four of these response variables as a function of the gMax's design and operating parameters.

$$\text{Log (Undersize Bypass)} = 0.7372 - 0.1747*B + 0.4635*C \qquad [4]$$

$$\text{Log (Oversize Bypass} + 0.10) = 7.7527 + 0.016*A - 3.9724*B - 0.9024*C + 0.4417*B^2 - 0.0036*A*B + 0.203B*C \qquad [5]$$

$$d50_c = 39.7634 - 0.122*A + 8.7968*B - 7.9069*C \qquad [6]$$

$$d95_c = 35.2939 + 1.8864*A + 0.7571*B - 26.8017*C - 4.1385*B{}^\wedge 2 - 0.7459*A*C + 19.3943*B*C \qquad [7]$$

Where A = Feed Pressure; B= Vortex Finder ; C= Spigot

Although excellent *imperfection* and *selectivity index* values were obtained from this test program, suitable model equations could not be developed to appropriately predict these response variables.

The perturbation plots shown in Figure 9 indicate the relative insignificance of the feed pressure on the various performance parameters over the values tested. Apex or spigot diameter and the vortex finder diameter appeared to have significant effect on the *undersize bypass*, whereas *oversize bypass* was mainly controlled by vortex finder diameter alone. The $d95_c$ particle size is more affected by the spigot diameter, whereas the $d50_c$ particle size is more affected by the vortex finder diameter. The only performance parameter for which the feed pressure may have some effect is the $d50_c$ particle size.

Using the empirical model equations, appropriate sets of experimental conditions were identified to achieve target separation performances as shown in Figure 7 of Appendix-I. As illustrated in Figure 8 of Appendix-I, the observed and predicted classification performances are fairly close both for the Box-Behnken tests and the model validation tests conducted after the development of the models.

Task 3: Cyclowash Evaluation

Exploratory Test Program

The main objective of the Cyclowash application was to reduce the amount of undersize bypass and thus improve the classification efficiency. The gMax cyclone study discussed in the previous section indicates that by optimizing the operating and design parameter values, the under size bypass could be reduced even without having the Cyclowash attachment to less than 10% level, however with relatively inferior *imperfection* and *selectivity index* values.

To conduct a preliminary evaluation of the effectiveness of the Cyclowash, it was desired to set the gMax parameters at a condition, which was known to provide poor classification performance, comparable to what is obtained with the 6-inch cyclone in the plant. The parameters selected were 1.5 inch, 1.0 inch and 23.5 psi for vortex finder diameter, spigot diameter and the feed pressure, respectively. The classification performance produced using this base condition included 30% of *undersize bypass*, *d50c* value of 32 micron, imperfection and selectivity index values of 0.46 and 0.33, respectively. As shown in Table 9 of Appendix-II, twelve exploratory tests were conducted with the Cyclowash by varying only truncated cone diameter and thus the angle and the elutriation water rate. Based on the resulting classification data, following conclusions are made:

- The undersize bypass was reduced to nearly 1% from 30% with some specific test conditions. The respective improvement of the corrected imperfection and selectivity values were from 0.46 to 0.24 and from 0.33 to 0.63.

- The d50c size was increased from 32 micron to 45 micron.

- The under size bypass increased with the use of increasing truncated cone sizes. The classification performance with large truncated cone diameter was even worse than the base gMax performance.

- The Cyclowash attachment did not have any effect on the oversize bypass.

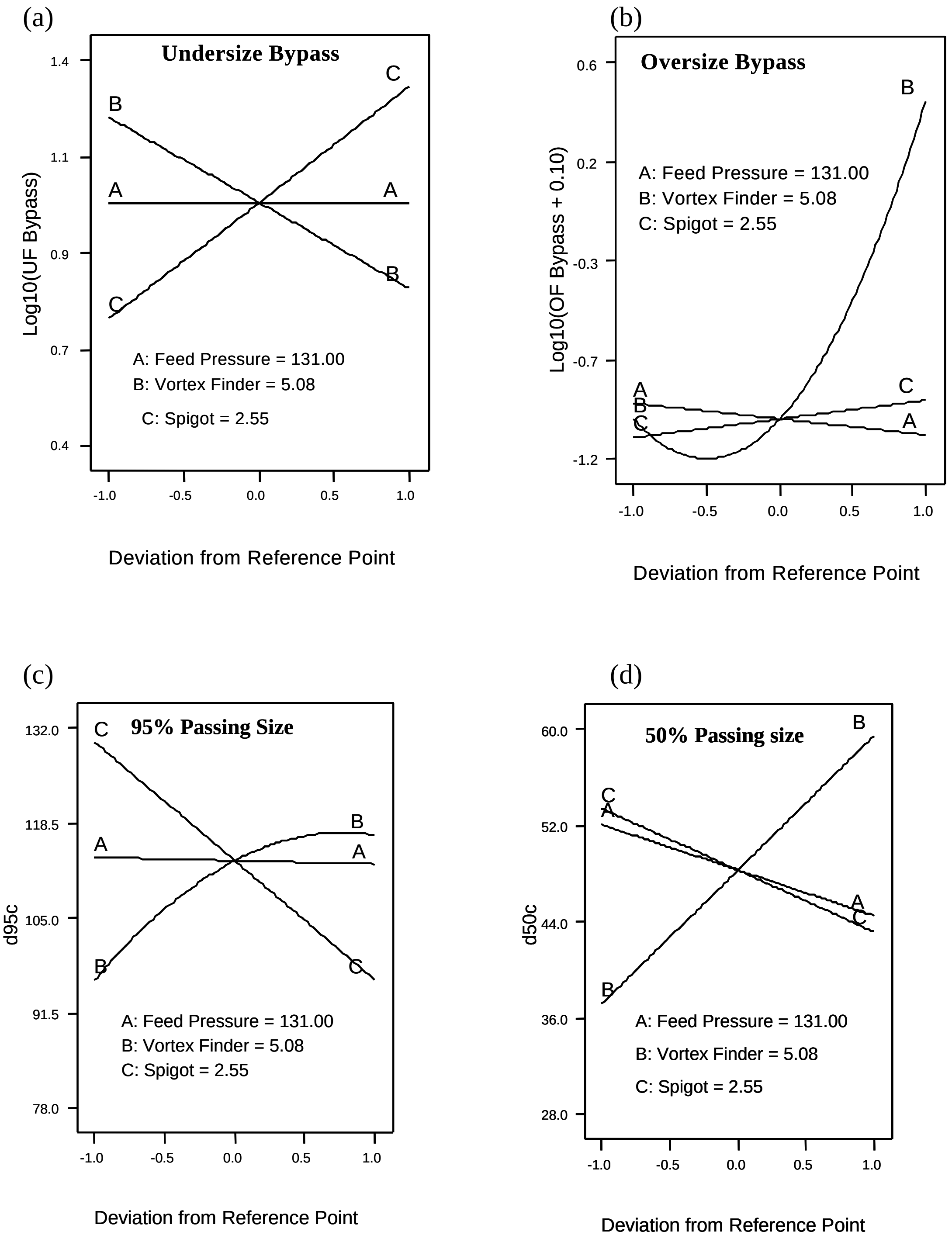

Figure 9: The perturbation plots for the selected performance parameters of gMax cyclone.

Plackett-Burman Design Test Program

To determine which factors have significant effect on the Cyclowash performance, twelve tests were conducted as a part of a Plackett-Burman experimental program using the parameter values listed in Table 10 of the Appendix-II. A statistical analysis of the experimental data determined the key operating and design parameter values, which affect various performance parameters as shown in Table 7. As shown, the main parameter effects for all five performances evaluated were caused due to feed pressure, vortex finder, truncated cone diameter and elutriation water rate. Hence, these four parameters were further investigated during the subsequent optimization test program.

Optimization Test Program

A Box-Behnken experimental program with four factors was designed to optimize the classification performance achievable from the Cyclowash. A list of operating parameter values used for each experiment is provided in Table 9 of Appendix-II. As shown, the feed pressure was varied over a range of 100 kPa (14.5 psi) to 162 kpa (23.5psi), whereas the vortex finder diameter over 3.81 cm (1.5 inch) to 6.35 cm (2.5 inch). Similarly the range of values used for the truncated cone diameter and the elutriation water flow rate are from 2.54 cm (1 inch) to 5.08 cm (2 inch) and 0 to 150 lpm (40 gpm), respectively. The test results are listed in Table 10 of Appendix-II, which shows some of the excellent classification performance with nearly 0 bypass for both undersize and oversize.

Empirical models were developed for six different performance parameters, including *imperfection*, *selectivity index*, *undersize bypass*, *oversize bypass, d50c* and *d95c*. The model equations are as follows:

$$\text{Imperfection} = -0.052 + 0.0154*A - 0.099*B - 0.0099*C - 6.2\text{E-}05*A^2 + 2.35\text{E-}05*A*C + 0.0016*B*C \qquad [8]$$

$$\text{Selectivity Index} = 0.774 - 0.012*A + 0.085*B + 0.009*C + 4.85\text{E-}05*A^2 - 2.16\text{E-}5*A*C - 0.0014*B*C \qquad [9]$$

$$\text{Sqrt (Undersize Bypass)} = 8.3809 - 1.52125*D + 0.976*B - 0.021*C \qquad [10]$$

$$\text{Oversize Bypass} = 114.79 - 0.9137*A - 25.241*D + 0.0175*C + 0.0033*A^2 + 2.9461*D^2 \qquad [11]$$

$$d95_c = 97.97 - 0.0417*A + 15.7301*D - 13.1562*B + 0.1169*C - 1.7226*D^2 - 0.00025*C^2 + 1.7825*D*B - 0.0209*D*C + 0.01837*B*C \qquad [12]$$

$$1.0/(d50c) = 0.0013 + 3.66\text{E-}05*A - 0.004*D + 0.0153*B - 4.09\text{E} - 05*C - 0.0016*B^2 \qquad [13]$$

where, A = Feed pressure; B=Cone diameter; C= Water flow rate; D= vortex finder

Table 7: A list of key operating and design parameters having significant effect on individual classification performances; A: Feed pressure; B: Vortex Finder; C: Spigot Diameter; D: Cone diameter; E: Injection water rate

Performance Parameters	Affecting Key Operating Parameters
Imperfection	BE and AC
Selectivity Index	AC and AE
Undersize Bypass	B and E
Oversize Bypass	B, D and E
$d50_c$	B, A and E

The perturbation plots shown in Figure 10 illustrates the importance level of various operating parameter effects on individual performance parameters. The *imperfection* and *selectivity index* responses are more affected by elutriation water flow rate and feed pressure than truncated cone diameter. The vortex finder diameter has a very negligible effect on these two responses; however has the maximum effect on the undersize and oversize bypass as well as $d95_c$ particle size. The truncated cone diameter has the maximum effect on the $d50_c$ particle size. The other parameters affecting the $d50_c$ particle size include elutriation water flow rate and vortex finder diameter.

Using the empirical model equations, appropriate sets of experimental conditions were selected to achieve target classification performances as shown in Figure 9 of Appendix-I. Additional tests were conducted to further validate the empirical model equations. As illustrated in Figure 10 of Appendix-I, the predicted values for four important performance parameters including *imperfection*, *selectivity index, undersize bypass* to the underflow and *oversize bypass* to the overflow are reasonably close to the experimentally observed values.

Performance Comparison:

Upon optimizing the performance of each new technology, the best classification performances were compared among the various new and existing technologies and the results are presented in Table 8 and Figure 12.

The classification performances for a separation particle size of 100 mesh were compared among the 15-inch classifying cyclone and Sieve bend technologies currently being used in the plant and the new Pansep screening technology. As shown, both 15-inch classifying cyclone and the sieve bend allow a significant amount of undersize material, i.e., 29.6% and 38%, respectively, to bypass the classification/screening process and report directly to the product streams. The respective imperfection and selectivity index values, which indicate the sharpness of size separation, are 0.57 and 0.27 for the 15-inch cyclone and 0.33 and 0.51 for the sieve bend. The size separation performance of the Pansep screen obtained from the treatment of the 15 inch cyclone feed slurry are significantly better than that of the 15 inch cyclone performance. The performance highlights are undersize bypass of 1.8%, imperfection value of 0.16 and the selectivity index of 0.73. For the Pansep treatment of the plant sieve bend feed material, the best screening

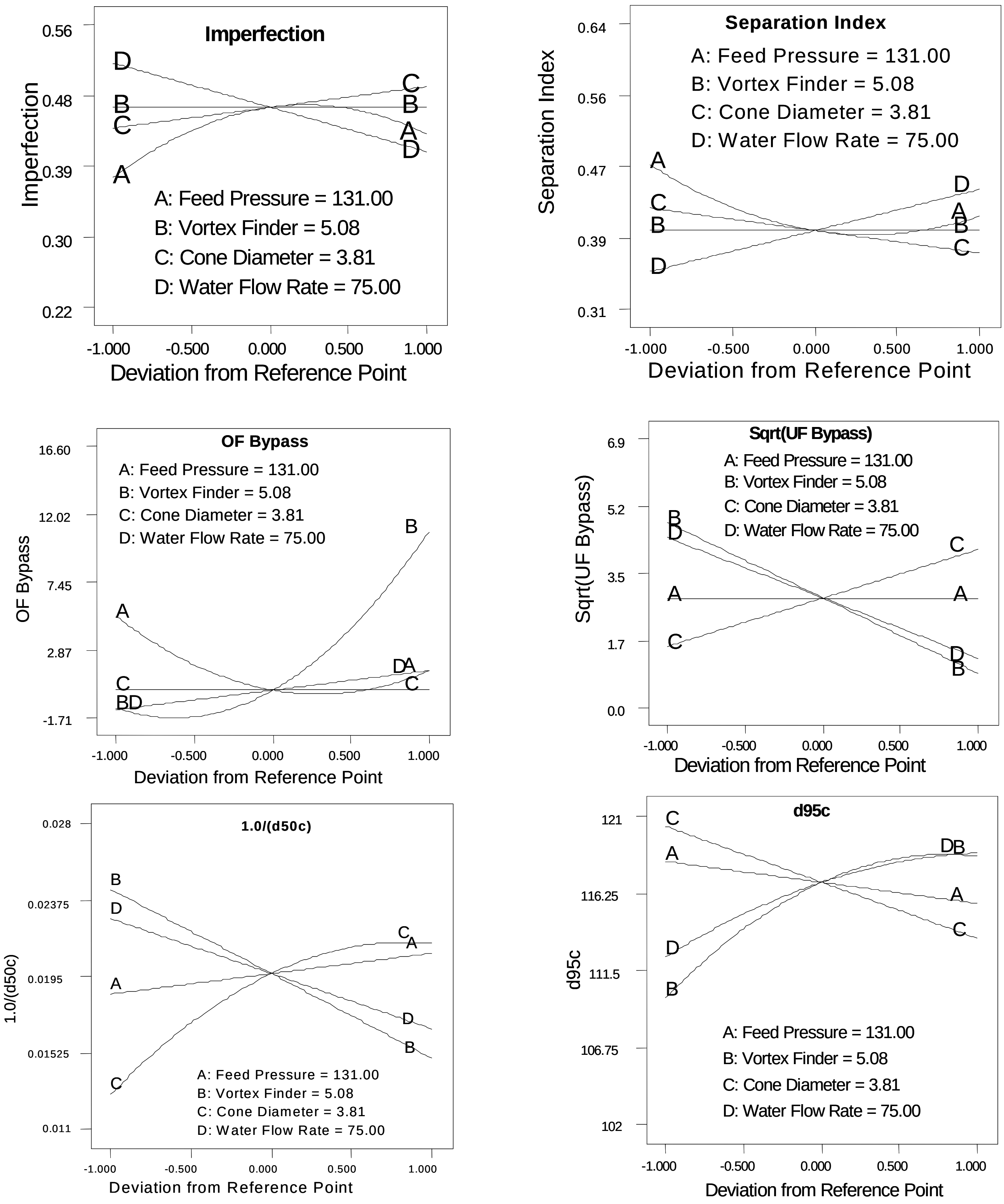

Figure 10: Perturbation plots for the six response variables (performance parameters) evaluated in the investigation.

Table 8: Performance comparison among the existing and new screening/classification technologies.

Technology	Undersize Bypass (%)	Oversize Bypass (%)	Imperfection	Sel. Index	d95c (micron)	d50c (micron)
15 inch Cyclone vs Pansep						
15"CYCLONE	27.3	1.71	0.65	0.28	300	72
PANSEP-I	1.8	0	0.16	0.73	280	146
PANSEP-II	3.3	0	0.17	0.69	295	160
Sieve Bend vs Pansep						
SIEVE BEND	21.5	0.20	0.15	0.75	375	138
PANSEP-I	2.8	0	0.26	0.61	280	145
PANSEP-II	1.8	0	0.23	0.64	305	155
6 " Cyclone vs gMAX vs Pansep vs Cyclowash						
6"CYCLONE	32.0	2.67	0.30	0.60	155	50
gMAX	15.3	0	0.27	0.58	83	41
PANSEP	0.4	0	0.20	0.68	69	47
Cyclowash	0	0	0.22	0.64	121	88

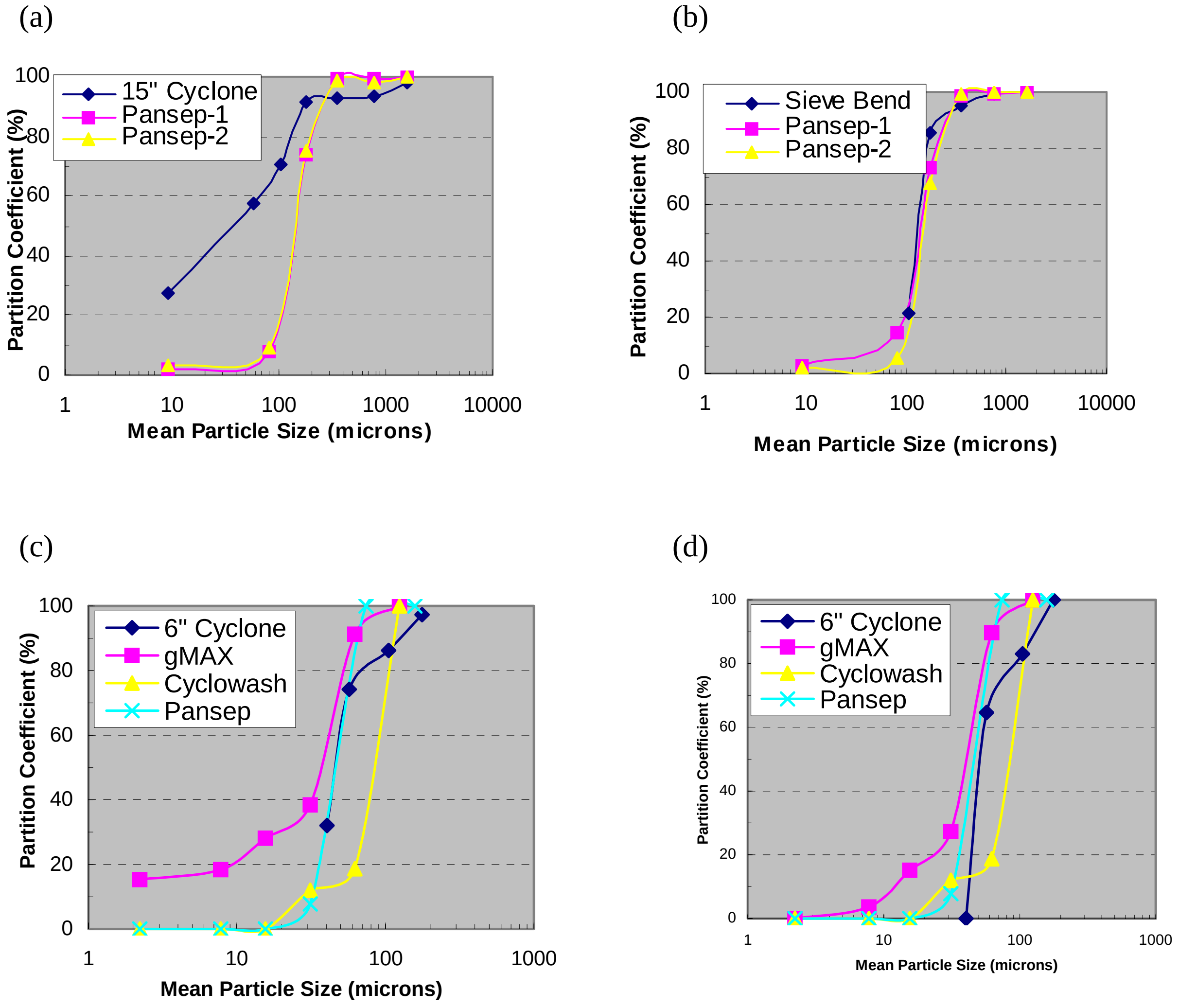

Figure 12: (a) 15 inch cyclone vs Pansep; (b) Sieve bend vs Pansep; (c) 6 inch Cyclone vs gMax vs Cyclowash vs Pansep (Uncorrected); (d) 6 inch Cyclone vs gMax vs Cyclowash vs Pansep (Corrected).

performance obtained includes an undersize bypass of 1.85, imperfection of 0.23 and a sharpness index of 0.64. The presence of a significantly higher amount of minus325 mesh particle size fraction in the sieve bend feed material may have caused the slightly inferior Pansep results obtained for the treatment of the sieve bend feed material in comparison to that of the 15-inch Cyclone feed materials.

The classification performances for 325-mesh particle size separation are compared among the 6-inch desliming cyclones operating in-plant, Krebs Engineers' new design gMax Cyclone with and without the Cyclowash attachment. As indicated in Table 19 and Figure 11, the 6-inch desliming cyclone operating in the plant allowed a significant amount of material bypass to both overflow and underflow streams. Nearly 32% of the undersize material and 17% of the oversize materials bypassed the classification process and directly reported to the underflow and overflow stream, respectively. These bypass amounts were reduced to nearly 15% for the undersize material and nil for oversize material with the use of the new design gMax cyclone. Both bypass values were reduced to zero by the use of Krebs Cyclowash with gMax cyclone; however, the $d50_c$ separation size was considerably increased. This was achieved with nearly 150 lpm of elutriation water provided to the Cyclowash system. A simple analysis indicates that a significant portion of this water reports to the cyclone overflow, which means an increased upward velocity inside the cyclone. This increase in upward velocity allows the coarser particles reporting to the overflow and thus results in a coarser d50c particle size. Thus, the existing design of Cyclowash may necessitate some design modification so that the undersize bypass can be mostly eliminated by the use of as small amount of water as possible.

Task 4: Economic Analysis:

The improved sizing efficiency of the new technologies results in reduced misplacement of particles to the overflow and underflow streams. In other words, the recovery of undersize material to screen underflow or cyclone overflow as well as the recovery of oversize material to the screen overflow or cyclone underflow are significantly improvement. To determine the monetary benefit that could be realized due to this improvement in fine coal sizing an economic analysis has been conducted for the 100 mesh size separation achieved at an Illinois coal preparation plant, whose details are provided in Table 9.

As indicated, the fine coal cleaning circuit of the plant treats 370 tph, which is classified at 100 mesh using 16 of 15 inch diameter classifying cyclones. The number of industrial size Pansep screens that will be required for this task is 8 (Buissman, 2001). The annualized capital cost has been calculated by discounting the total capital cost at 12% over a period of 15 years. The capital and operating cost calculation includes the cost for the ancillary equipments as well. For example, while calculating the cost of cyclones, the pump, sump, feed distributor and piping costs were also included. As shown, the total annual capital and operating cost for size separation option is significantly higher than that with the existing technology. A similar cost analysis for the spiral product desliming

Table 9: A comparative cost analysis for 100 mesh size separation

Feed rate to the fine circuit: 370 tph; 11000 gpm		Annualized Capital Cost ($)	Annual Operating Cost ($)	Total Annual Cost ($)
No. of 15 inch Cyclone used in the plant	16	27, 974	20, 100	48, 074
No. of 9 m^2 Pansep units required	8	88, 080	96, 000	184, 000
Spiral product rate: 200 tph				
No. of Sieve bend and VariSieve used in plant	4, 2	10, 630	43, 440	54, 070
No. of 9 m^2 Pansep units required	4	43, 800	48 000	91 800

at 100 mesh using a Sieve bend-VariSieve combination versus Pansep screen also indicates the higher capital and operating cost for the Pansep option.

However, a benefit analysis described in the following paragraph will indicate that, although the new technology integration will cost significantly higher than the old ones, the resulting improved size efficiency will prevent the loss of significant amount of misplaced clean coal to the plant thickener. The resulting additional revenue due to the recovery of additional clean coal will far offset the increased cost of the new technologies and increase the plant profitability.

The preparation plant used in this study rejects the underflow of the Sieve bends, which screen the spiral product, supposedly, for removing relatively high ash fine material. This means that the –100 mesh fine coal misplaced to the cyclone underflow, which bypasses the spiral cleaning process is ultimately rejected to the plant thickener causing a significant loss of valuable fine coal. A simple analysis indicates that due to the high proportion, i.e., nearly 40% of –100 mesh material misplaced to the cyclone underflow, nearly 57 tph of misplaced fine coal having an ash content of 39% is lost to the plant thickener. This loss could be reduced to only 3 tph by using Pansep screens in place of the banks of 15 inch cyclones in the plant. Thus, additional 54 tph fine coals could be recovered. Based on a $1.05 /mbtu and 8000 btu/lb for the high ash coals on a dry basis as well as nearly 7000 hrs of working hours a year, nearly $ 6.7 millions of additional revenue could be generated every year. Understandably this will far offset the increased annual cost of $136, 000 incurred due to the new technologies and result in increased plant profitability.

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

The main objective of this study was to evaluate some of the state of the art screening and classification device to improve fine coal sizing performance in the Illinois coal preparation plants, which could improve the overall plant profitability. The new technologies studied in this investigation includes the Pansep screening technology, Krebs' new design gMax cyclone and the Cyclowash attachment with an industrial size cyclone. The Pansep screen's performance has been evaluated for 100 mesh particle size separation and compared with the performances of sieve bend and 15 inch cyclones operating in an Illinois coal preparation plant. The performance of 6-inch gMax cyclone and the Cyclowash attachment and the Pansep screen has been evaluated for 325 mesh size separation and compared with the 6-inch cyclone of conventional design operating in an Illinois coal preparation plant. The conclusions of this study can be summarized as follows:

Pansep Screen:

1. The optimized Pansep screen performance is significantly better than the performance of 15-inch cyclone for classifying the minus1 mm particle size slurry at 100 mesh. The undersize bypass was reduced from nearly 27% with 15-inch cyclone to nearly 2% with the Pansep screen. The corresponding improvement in the sharpness of size separation is indicated by an improvement in the corrected *imperfection* and *selectivity index* values from 0.65 and 0.28 to 0.16 and 0.73, respectively while achieving nearly the same $d95_c$ separation size.

2. The Pansep screen performance was also found to be significantly better than the plant VariSieve performance. The undersize bypass of nearly 22% from the sieve bend was reduced to nearly 2% with the Pansep screen. This resulted in a significant improvement of overall efficiency from nearly 44% from plant the VariSieve to nearly 98% with the Pansep screen. Although, the oversize recovery to the overflow of the VariSieve is nearly 96%, the undersize recovery to the underflow is extremely low.

3. A near perfect efficiency of 99% was achieved from the Pansep screen for the 325 mesh size separation in comparison to a poor 38% from the Plant 6-inch diameter Cyclone. The poor efficiency values results from the plant cyclone due to nearly 32% of underflow bypass and nearly 3% of the overflow bypass.

4. The fractional factorial design test program conducted using the Pansep screen identified the critical operating parameters to be feed flow rate, screen traveling speed, water spray angle and feed solid contents. The spray water volume was not found to be significant in the range of 15 to 25 gpm tested.

5. The optimization test program conducted utilizing Box-Behnken design illustrated the relative significance of the key operating parameters for individual performance parameters. Feed flow rate was found to have the maximum effect on selectivity index and imperfection value, whereas screen traveling speed and spray angle have the maximum effect on the undersize bypass. The feed solids content had the maximum effect on the 325 mesh separation performance of the Pansep screen.

6. The 100 mesh particle size separation performance achieved by the Pansep screen for the sieve bend feed material was found to be slightly inferior than that achieved by 15 inch cyclone feed material. It is believed that high concentration of minus325 mesh ultrafine material in the sieve bend feed slurry may have negatively affected the rheological property, thus slightly impacting the screening performance of the Pansep screen.

gMax Cyclone:

1. The gMax cyclone recently developed by Krebs Engineers to particularly address the fine classification issues appear to produce significantly better result than the conventional design. The comparative results obtained for near 325 mesh particle size classification using 6 inch diameter cyclones indicate that the undersize and over size bypass amounts were reduced from nearly 32% to 12% and 3% to nil respectively. The corrected imperfection and selectivity index value for both conventional and new designs are nearly the same.

2. The gMax optimization studies indicate that undersize bypass amount is almost equally affected by the vortex finder and the spigot diameters, where as the oversize bypass is mostly affected by the vortex finder diameter only. The feed slurry pressure over the range of 14.5 to 23.5 psi had the minimum effect on many performance parameters. The $d50_c$ separation size is the only performance, which appears to be having some appreciable effect of the feed slurry pressure. Interestingly, $d95_c$ separation size is the least affected by the feed slurry pressure.

3. The gMax design of Cyclone is a significant improvement over the conventional cyclone design as indicated by the significant reduction in the particle misplacements.

Cyclowash:

1. Further improvement in the 325 mesh classification performance was achieved with the use of Cyclowash in the 6 inch diameter gMax cyclone. Both undersize and oversize bypass were completely eliminated while improving the imperfection and selectivity index values from 0.34 and 0.56, respectively, to 0.22 and 0.64, respectively.

2. A Plackett-Burman factorial design conducted using the Cyclowash identified the four operating parameters, i.e., vortex finder diameter, feed slurry pressure, truncated cone diameter and elutriation water rate, having significant main effects on the classification performance. The spigot diameter tested over a range of 0.75 to 1.25 inch was found not having significant main effect on any on the performance parameters evaluated.

3. The optimization experiments conducted pursuing a Box-Behnken design test program indicated the relative significance of the key process parameters selected. The elutriation water rate had the maximum effect on the undersize bypass, imperfection and selectivity index, whereas the vortex finder diameter had the maximum effect on the oversize bypass. The truncated cone diameter and the vortex finder diameter, jointly had the maximum effect on the $d50_c$ separation size.

4. The undersize-bypass to the underflow and oversize bypass to the overflow were nearly completely eliminated using relatively high amount of injection water rate; however, the increased water rate increased the $d50_c$ separation size significantly. At the same $d50_c$ values the imperfection and selectivity index values for the Cyclowash was slightly inferior to the gMax performance.

Recommendations:

1. Due to the constraints with the experimental set-up, the pressure of the water spray could not be varied from nearly 10 psi for the Pansep evaluation. Higher spray pressures would be necessary to increase feed throughput capacity while maintaining a high efficient screening performance. This phenomenon may be further investigated for maximum through put capacity from the Pansep screen. With a higher capacity the Pansep screen will be better placed as the size separator for the enhanced gravity separators.

2. The excellent classification performance from the Pansep screen needs to be verified in a plant environment. One other potential area of investigation for Pansep screen could be for the improved magnetite recovery from the heavy media circuit.

3. A better design of Cyclowash needs to be investigated so that the maximum reduction in undersize bypass can be achieved without significantly affecting the $d50_c$ size separation.

ACKNOWLEDGEMENT

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Appendix- I

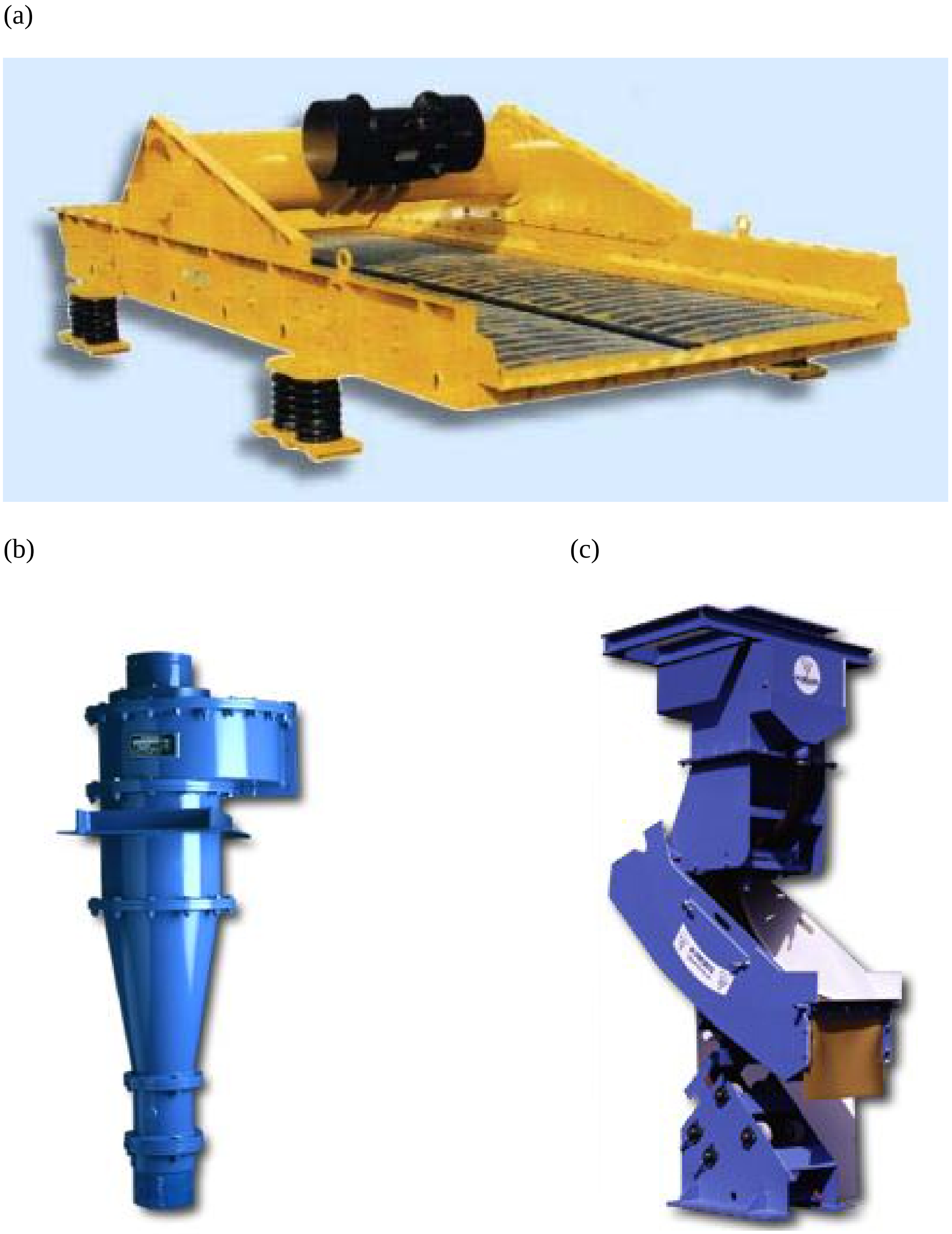

Figure 1: Conventional technologies used for fine coal screening in the Illinois coal preparation plants. (a) Vibratory screen; (b) Classifying cyclone; (c) Sieve bend (Krebs' VariSieve^{TM})

Figure 2: Pictures of (a) the Pansep screen used in this study (2) the experimental layout used for the evaluation of the Pansep screen.

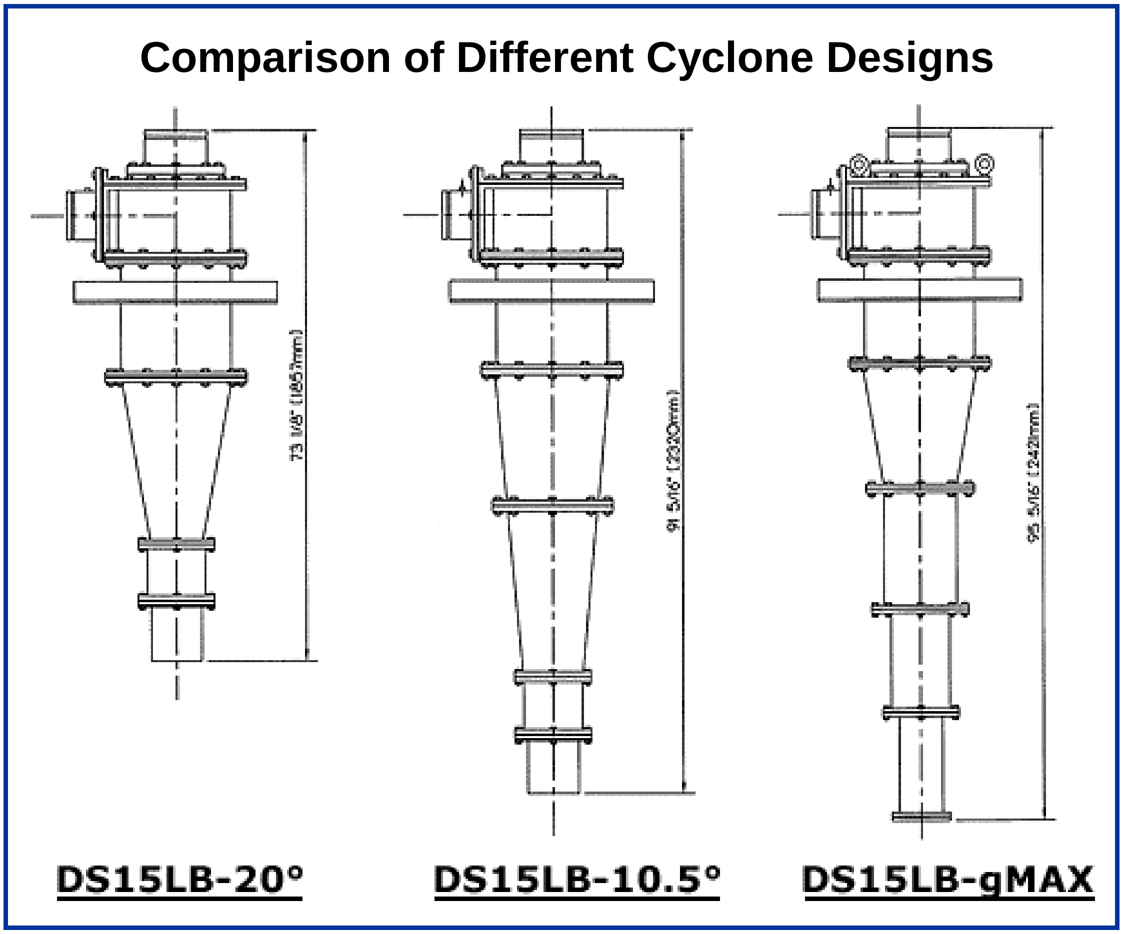

Figure 3: Geometric comparison of gMax cyclone with the traditional Krebs' cyclone design.

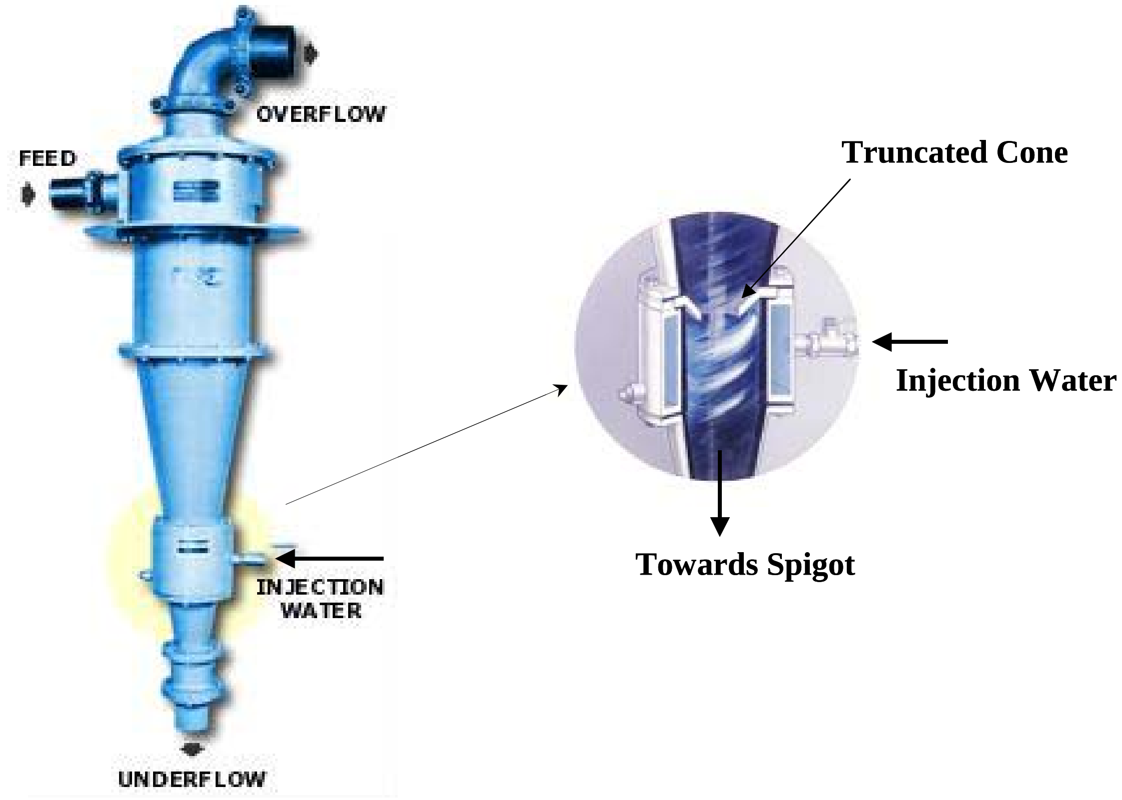

Figure 4: Krebs' Cyclowash: outside and inside view (Krebs, 2001)

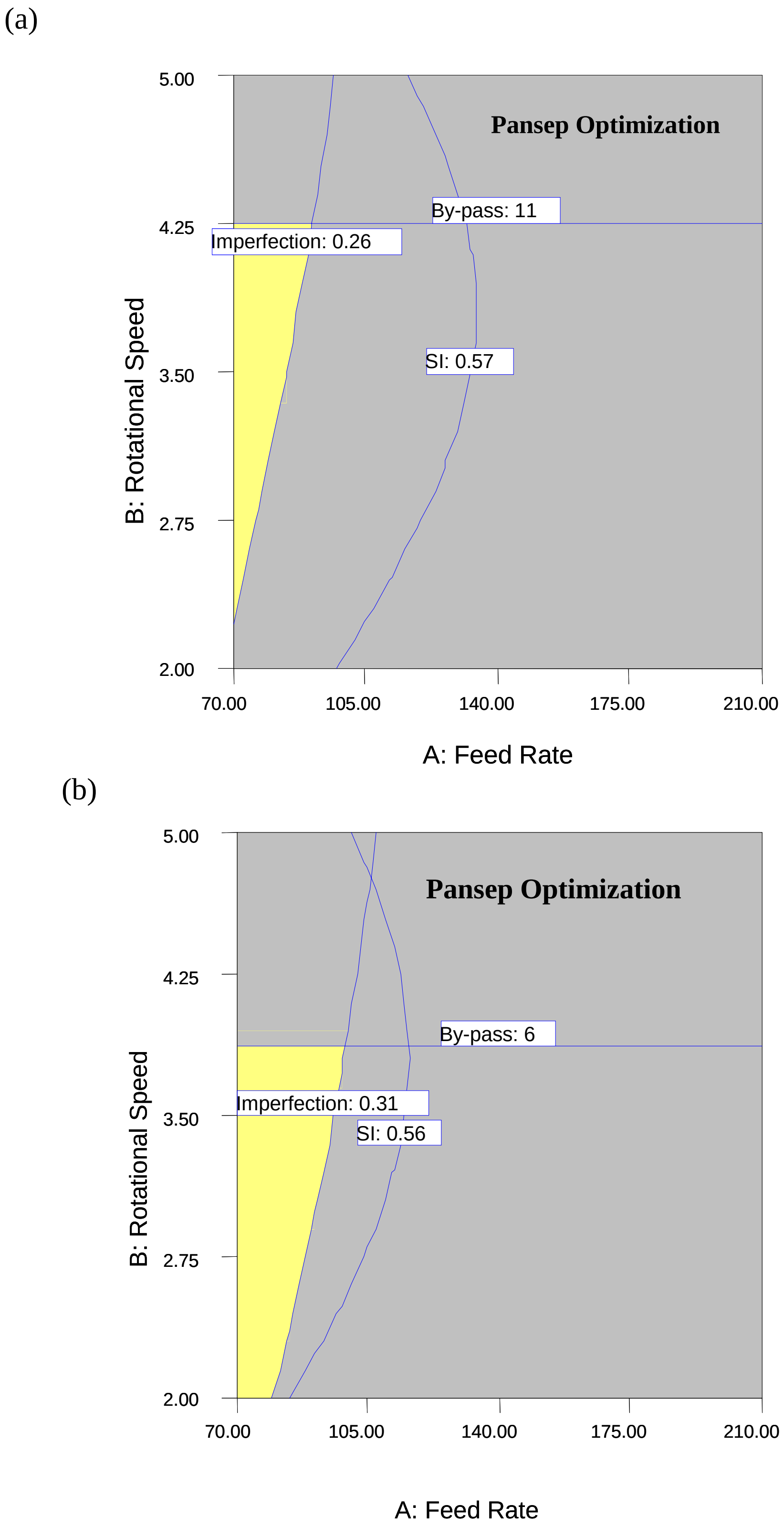

Figure 5: Optimization of Pansep parameters for achieving the desired target screening performances.

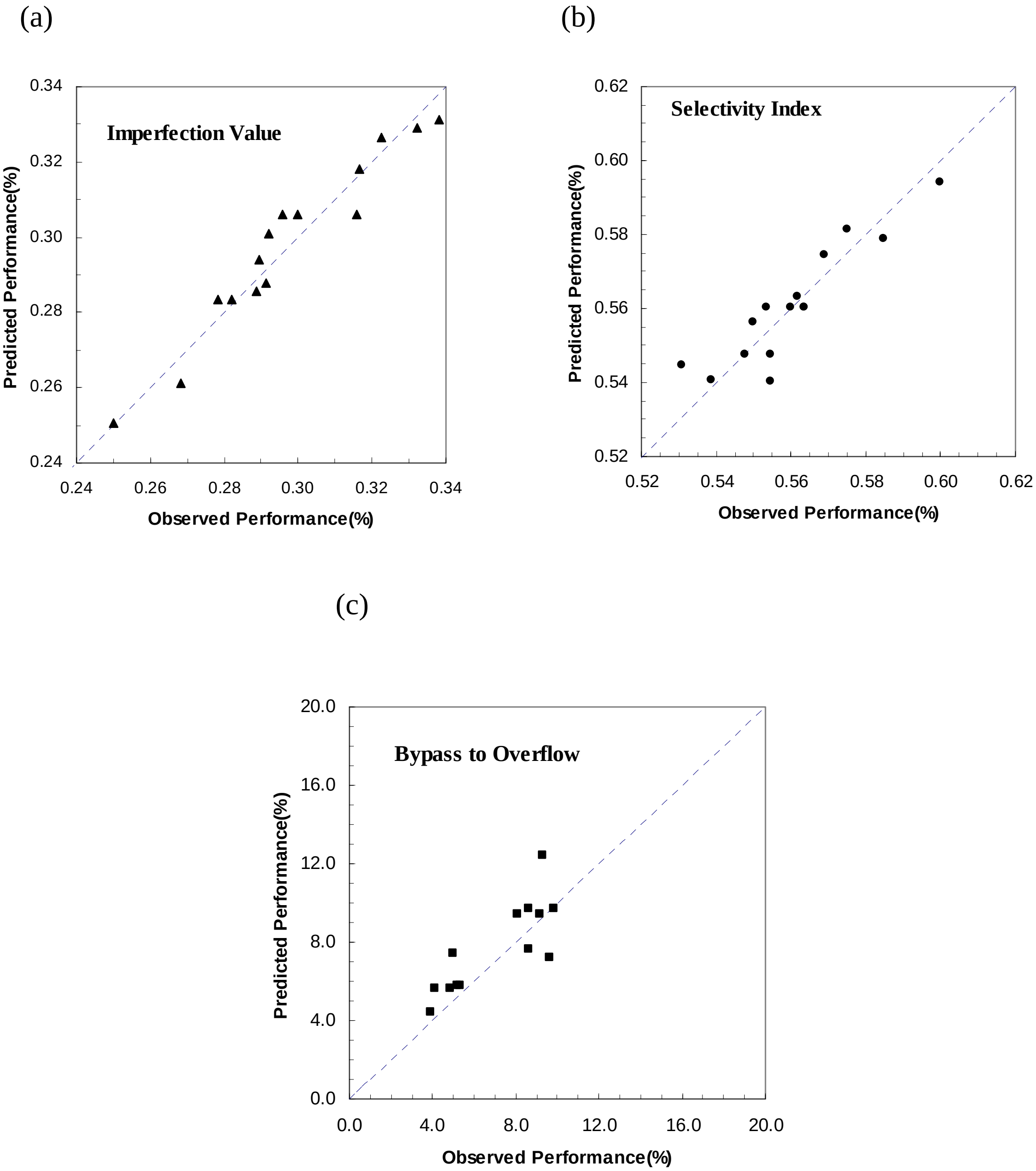

Figure 6: Predicted versus the observed performance parameter values to validate the empirical models.

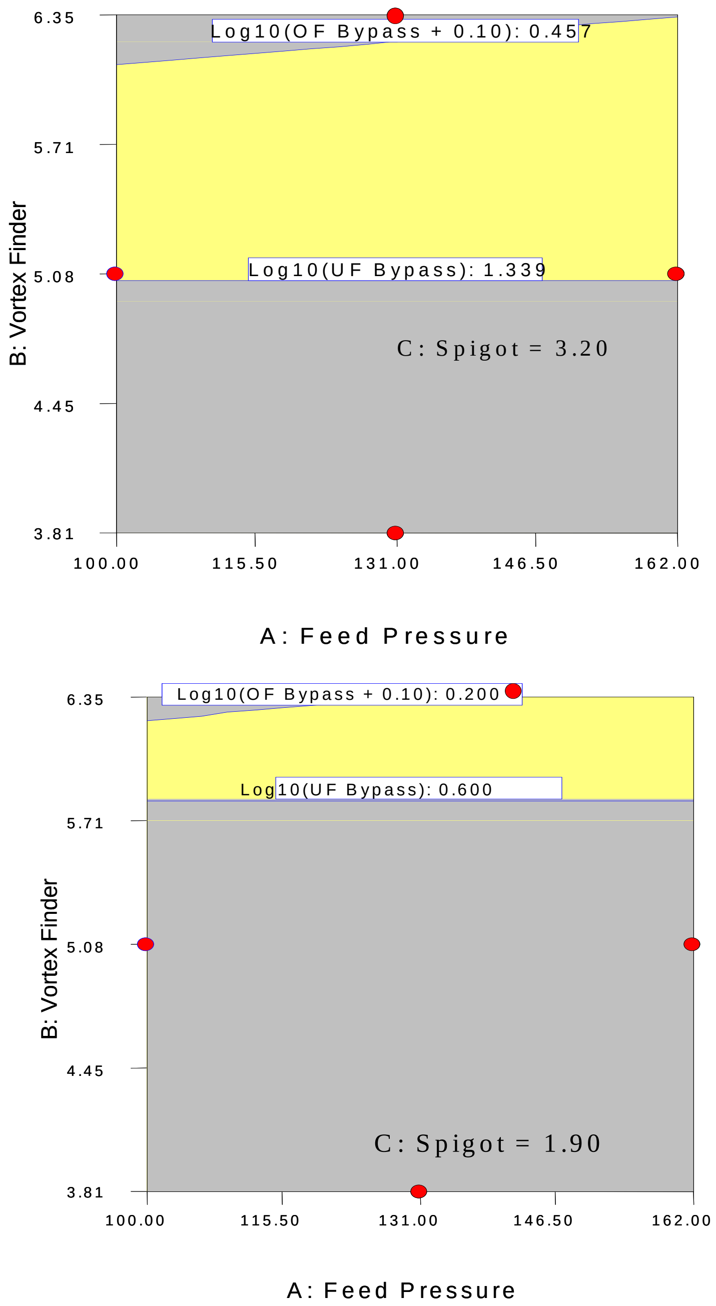

Figure 7: gMax optimization plots

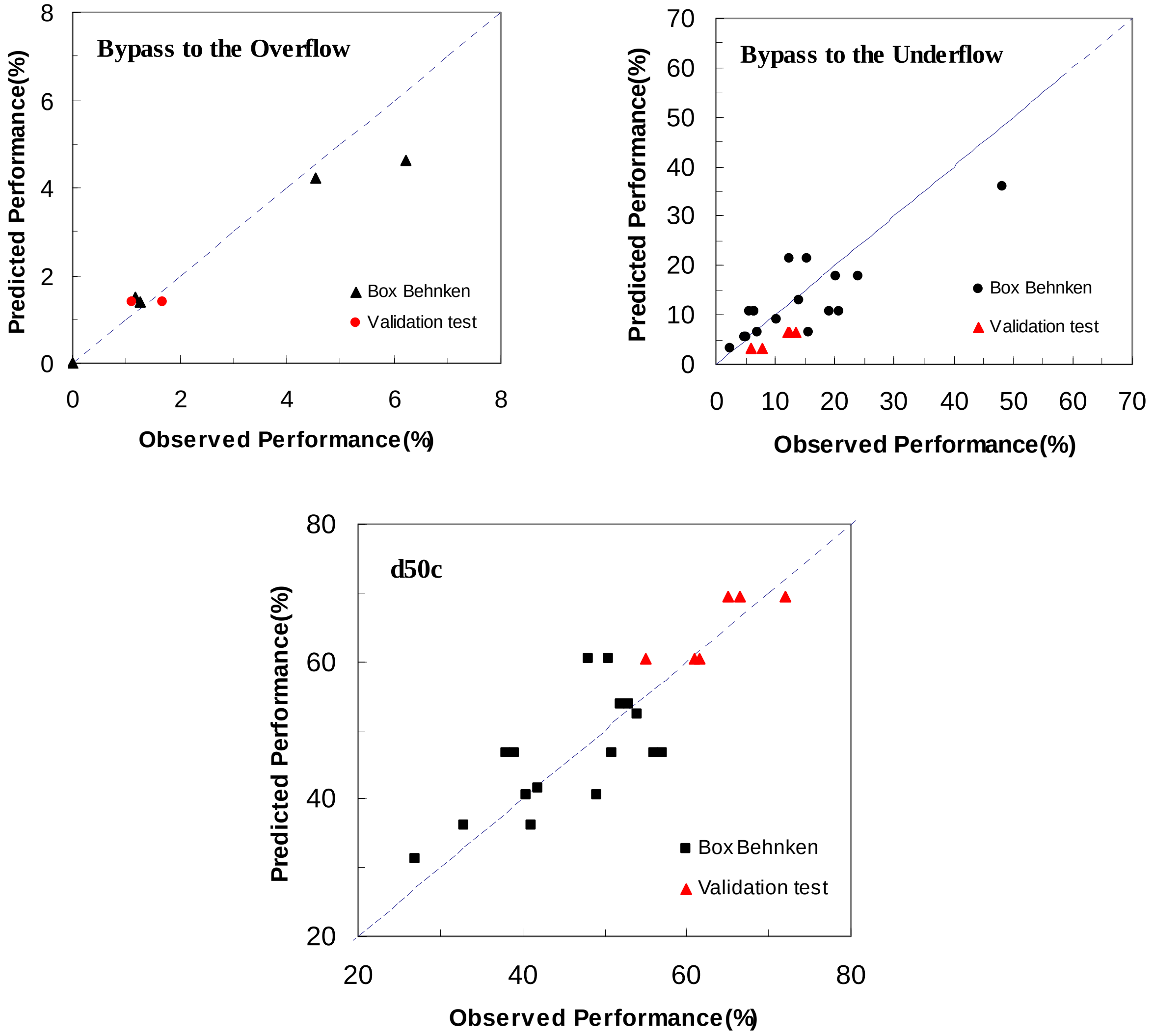

Figure 8: Model validation plots for gMax

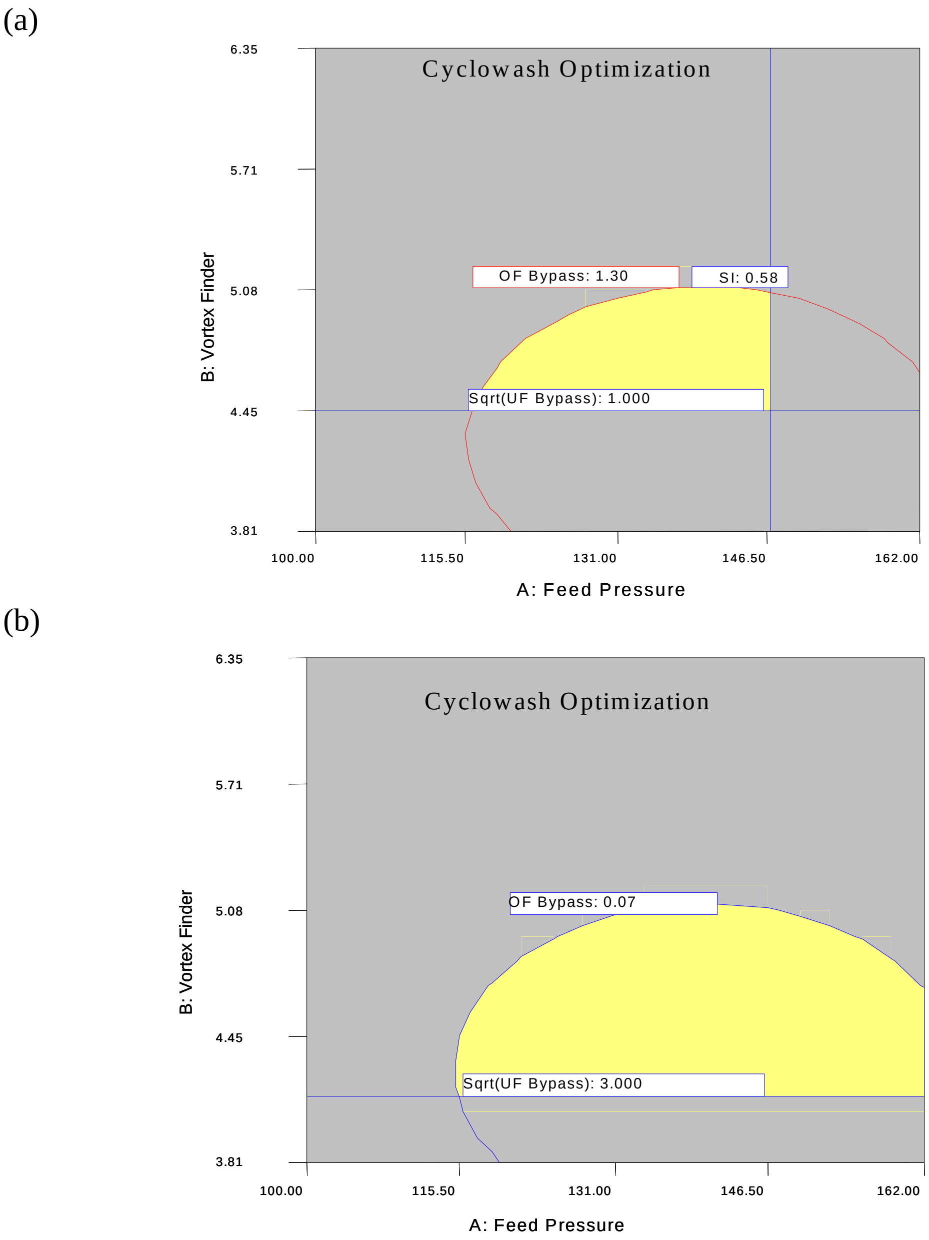

Figure 9: Optimization plots for Cyclowash

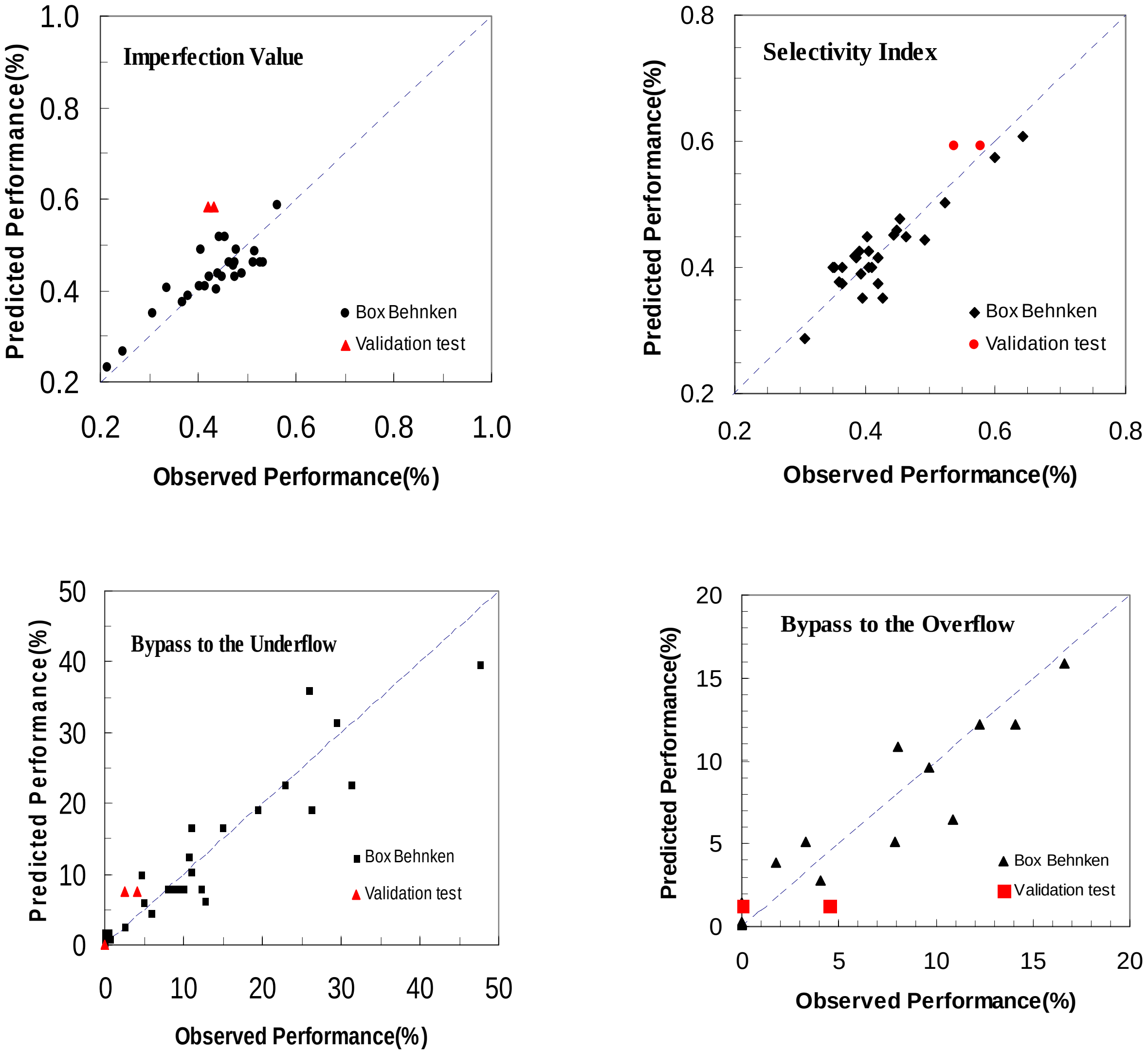

Figure 10: Comparison of predicted versus observed values for four performance parameters.

Appendix-II

Table 1: Exploratory tests conducted by varying the feed flow rate and the screen speed of the Pansep screen. The constant parameters were spray water at 100 lpm, feed solid content at 13% and angle of spray at 0^o.

Operating Parameter Values			**Results**			
Test #	Feed Flow (lpm)	Speed (rpm)	Undersize Bypass (% weight)	d50c (micron)	Imperfection	Selectivity Index
1	98	1.7	1.6	150	0.20	0.68
2	98	4.2	3.1	140	0.19	0.68
3	210	1.7	5.9	215	0.29	0.54
4	210	4.2	8.6	140	0.17	0.70

Table 2: Exploratory tests conducted by varying the feed flow rate and the water spray angle with the Pansep screen. The constant parameters were spray water at 75 lpm, feed solid content at 13% and screen rotational speed at 3 rpm.

Operating Parameter Values			**Results**			
Test #	Feed Flow (lpm)	Spray Angle (degree from vertical)	Undersize Bypass (% weight)	d50c (micron)	Imperfection	Selectivity Index
1	170	0	6.6	208	0.31	0.53
2	170	45	8.5	130	0.27	0.58
3	170	22.5	3.5	162	0.25	0.61
4	98	0	5.7	150	0.19	0.66
5	98	45	3.7	140	0.17	0.70

Table 3: Exploratory tests conducted by varying the feed solids content and the water spray angle with the Pansep screen. The constant parameters were feed rate at 170 lpm, water spray rate at 75 lpm and screen rotational speed at 3 rpm.

Operating Parameter Values			**Results**			
Test #	Feed Solids (% weight)	Spray Angle (degree from vertical)	Undersize Bypass (% weight)	d50c (micron)	Imperfection	Selectivity Index
1	14.0	0	5.7	160	0.20	0.64
2	14.0	45	8.5	130	0.27	0.58
3	6.2	45	3.3	160	0.17	0.69
4	6.2	45	3.5	165	0.20	0.66
5	6.2	45	5.1	160	0.16	0.71

Table 4: The operating parameter values used for the fractional factorial test program conducted with for 100 mesh size separation and the resulting performance parameters for the Pansep screen.

Operating Parameter Values					
Test #	Feed Flow	Feed Solids	Speed	Water Spray	Spray Angle
	(lpm)	(% weight)	(rpm)	(lpm)	(degree from vertical)
1	100	13.1	1	50	30
2	210	13.1	4	100	30
3	100	12.8	4	50	0
4	210	12.8	1	100	0
5	210	6.6	1	50	0
6	100	6.6	4	100	0
7	210	6.6	4	50	30
8	100	6.6	1	100	30
Results					
Test #	d50c	d95c	Imperfection	Selectivity	Oversize Bypass
	(micron)	(micron)		Index	(% weight)
1	128	280	0.35	0.45	9.8
2	145	310	0.31	0.55	11.9
3	230	360	0.23	0.62	5.7
4	130	300	0.37	0.44	34.1
5	170	325	0.31	0.54	6.8
6	155	305	0.23	0.64	1.8
7	180	330	0.28	0.58	9.7
8	185	400	0.32	0.54	4.1

Table 5: The list of operating parameters and their values used in the Box-Behnken design test program conducted with the Pansep screen for 100 mesh size separation along with the performance parameters resulted from each test.

Operating Parameter Values					
Test #	Feed Flow (lpm)	Feed Solids (% weight)	Speed (rpm)	Water Spray (lpm)	Spray Angle (degree from vertical)
1	70	10.0	3.5	75	0
2	210	10.0	3.5	75	0
3	140	10.0	5	75	0
4	140	10.0	2	75	0
5	140	10.0	3.5	75	15
6	140	10.0	3.5	75	15
7	210	10.0	5	75	15
8	140	10.0	3.5	75	15
9	140	10.0	3.5	75	15
10	210	10.0	2	75	15
11	140	10.0	3.5	75	15
12	70	10.0	2	75	15
13	70	10.0	5	75	15
14	70	10.0	3.5	75	30
15	140	10.0	2	75	30
16	140	10.0	5	75	30
17	210	10.0	3.5	75	30
Results					
Test #	d50c (micron)	d95c (micron)	Imperfection	Selectivity Index	Undersize Bypass (% weight)
1	152	306	0.29	0.58	4.1
2	170	330	0.34	0.53	4.8
3	152	306	0.32	0.55	9.6
4	170	330	0.33	0.54	3.9
5	145	280	0.26	0.61	2.8
6	195	330	0.30	0.55	5.0
7	180	330	0.32	0.55	9.2
8	186	330	0.30	0.56	13.1
9	152	380	0.32	0.56	11.0
10	154	330	0.29	0.55	5.2
11	160	325	0.24	0.61	11.6
12	172	330	0.28	0.57	5.3
13	190	340	0.27	0.58	8.1
14	152	302	0.25	0.60	8.6
15	187	360	0.29	0.55	8.6
16	185	340	0.28	0.56	9.3
17	170	325	0.29	0.56	9.8

Table 6: The operating parameter values used for the exploratory test program conducted for the 325 mesh size separation and the resulting performance parameters for the Pansep screen.

Operating Parameter Values					
Test #	Feed Flow (lpm)	Feed Solids (% weight)	Speed (rpm)	Water Spray (lpm)	Spray Angle (degree from vertical)
1	240	1.72	3	170	15
2	240	1.72	3	170	15
3	300	1.72	3	170	15
4	300	1.72	3	170	15
5	240	1.31	3	170	45
6	240	1.31	3	170	45
7	300	1.31	3	170	45
8	300	1.31	3	170	45
Results					
Test #	d50c (micron)	d95c (micron)	Imperfection	Selectivity Index	Oversize Bypass (% weight)
1	71.60	119.15	0.349	0.490	0.91
2	75.00	119.45	0.324	0.512	1.24
3	75.00	119.45	0.324	0.512	0.49
4	71.60	119.15	0.342	0.500	1.19
5	78.00	119.80	0.304	0.532	0.00
6	74.40	119.40	0.325	0.513	0.01
7	80.00	119.90	0.289	0.547	0.65
8	77.00	119.70	0.306	0.531	0.36

Table 7: The list of operating parameters and their values used in the Box-Behnken design test program conducted for 325 mesh size separation using a Pansep screen along with the performance parameters resulted from each test.

Operating Parameter Values					
Test #	Feed Flow	Feed Solids	Linear Speed	Water Spray	Spray Angle
	(lpm)	(% weight)	(mpm)	(lpm)	(degree from vertical)
1	240	3.0	13.5	170	0
2	110	1.0	13.5	170	0
3	240	2.0	18.0	170	0
4	175	1.0	9.0	170	0
5	175	2.0	13.5	170	0
6	175	3.0	9.0	170	0
7	175	3.0	18.0	170	0
8	175	2.0	13.5	170	0
9	110	3.0	13.5	170	0
10	240	1.0	13.5	170	0
11	110	2.0	18.0	170	0
12	110	2.0	9.0	170	0
13	240	2.0	9.0	170	0
14	175	2.0	13.5	170	0
15	175	2.0	13.5	170	0
16	175	1.0	18.0	170	0
17	175	2.0	13.5	170	0
Results					
Test #	d50c	d95c	Imperfection	Selectivity Index	Undersize Bypass
	(micron)	(micron)			(% weight)
1	104.2	152.4	0.274	0.56	0.91
2	48.2	69.4	0.179	0.70	0.36
3	86.0	151.0	0.391	0.45	0.36
4	47.0	68.8	0.196	0.68	0.36
5	84.0	150.5	0.393	0.45	0.36
6	51.5	101.2	0.218	0.65	1.19
7	112.5	153.5	0.209	0.65	1.24
8	51.0	86.0	0.206	0.67	0.01
9	105.0	152.6	0.263	0.58	0.49
10	46.6	68.6	0.200	0.67	0.36
11	87.5	151.2	0.375	0.46	0.36
12	58.0	144.6	0.414	0.46	0.36
13	50.2	103.5	0.239	0.63	0.65
14	58.0	145.0	0.435	0.45	0.36
15	78.0	150.0	0.413	0.45	0.36
16	48.0	69.2	0.182	0.70	0.36
17	50.0	78.5	0.198	0.68	0.00

Table 8: Operating parameter values used for each test conducted during the Box-Behnken test program conducted to optimize the performance of gMax cyclone and the resulting test data.

Operating Parameter Values				
Test #	Feed Pressure	Feed Flow Rate	Vortex Finder	Spigot
	(kPa)	(lpm)	(cm)	(cm)
1	100	355	5.08	3.2
2	162	490	6.35	2.55
3	100	300	5.08	1.9
4	131	401	5.08	2.55
5	131	440	6.35	3.2
6	131	354	3.81	3.2
7	131	340	3.81	1.9
8	131	401	5.08	2.55
9	100	395	6.35	2.55
10	131	401	5.08	2.55
11	162	442	5.08	1.9
12	131	401	5.08	2.55
13	131	400	5.08	2.55
14	131	451	6.35	1.9
15	162	379	3.81	2.55
16	162	446	5.08	3.2
17	100	297	3.81	2.55

Results						
Test #	d50c	d95c	Imperfection	Selectivity Index	Undersize Bypass	Oversize Bypass
	(micron)	(micron)			(% weight)	(% weight)
1	49	114	0.35	0.51	12.3	0.0
2	51	116	0.48	0.40	7.1	1.2
3	53	116	0.43	0.45	5.1	0.0
4	57	117	0.44	0.44	6.4	0.0
5	54	117	0.45	0.42	14.1	6.2
6	27	62	0.53	0.33	48.3	0.0
7	42	109	0.38	0.46	10.3	0.0
8	56	117	0.43	0.44	6.6	0.0
9	48	115	0.45	0.42	15.7	4.6
10	39	107	0.45	0.39	20.7	0.0
11	52	116	0.49	0.39	4.9	0.0
12	38	106	0.46	0.38	19.2	0.0
13	51	116	0.39	0.49	5.6	0.0
14	81	120	0.29	0.55	2.5	1.3
15	33	96	0.46	0.38	24.1	0.0
16	41	83	0.27	0.58	15.3	0.0
17	41	98	0.33	0.50	20.2	0.0

Table 9: The operating parameter values used for the exploratory tests conducted with the Cyclowash and the resulting classification performance values.

Operating Parameter Values					
Test#	Feed Pressure	Vortex Finder	Spigot Diameter	Cone Diameter	Water Flow Rate
	(kPA)	(cms)	(cms)	(cms)	(lpm)
1	162	3.81	2.54	2.54	0
2	162	3.81	2.54	2.54	75
3	162	3.81	2.54	2.54	113
4	162	3.81	2.54	2.54	150
5	162	3.81	2.54	3.81	0
6	162	3.81	2.54	3.81	75
7	162	3.81	2.54	3.81	113
8	162	3.81	2.54	3.81	150
9	162	3.81	2.54	5.08	0
10	162	3.81	2.54	5.08	75
11	162	3.81	2.54	5.08	113
12	162	3.81	2.54	5.08	150
Results					
Test#	d50c	Imperfection	Selectivity	Undersize Bypass	Oversize Bypass
	(micron)		Index	(% Weight)	(% weight)
1	44	0.39	0.47	16.6	0
2	44	0.40	0.45	9.5	0
3	60	0.45	0.40	5.5	0
4	45	0.24	0.63	0.6	0
5	34	0.35	0.45	36.9	0
6	35	0.34	0.44	23.6	0
7	41	0.40	0.42	19.2	0
8	42	0.33	0.50	12.5	0
9	35	0.40	0.43	42.0	0
10	39	0.42	0.38	32.3	0
11	37	0.41	0.41	23.7	0
12	29	0.45	0.41	44.4	0

Table 10: The operating parameter values and the resulting classification performance values generated from the Plackett-Burman experimental program.

Operating Parameter Values					
Test#	Feed Pressure	Vortex Finder	Spigot Diameter	Cone Diameter	Water Flow Rate
	(kPA)	(cms)	(cms)	(cms)	(lpm)
1	100	3.81	1.92	5.08	150
2	100	6.35	3.18	5.08	0
3	100	3.81	3.18	5.08	150
4	100	3.81	1.92	2.54	0
5	100	6.35	3.18	2.54	150
6	162	3.81	3.18	5.08	0
7	162	3.81	1.92	2.54	150
8	162	6.35	3.18	2.54	150
9	162	3.81	3.18	2.54	0
10	162	6.35	1.92	5.08	0
11	100	6.35	1.92	2.54	0
12	162	6.35	1.92	5.08	150
Results					
Test#	d50c	Imperfection	Selectivity Index	Oversize Bypass	Undersize Bypass
	(micron)			(% Weight)	(% Weight)
1	57	0.61	0.26	3.6	9.0
2	90	0.24	0.60	9.1	0.0
3	45	0.49	0.40	0.0	13.0
4	57	0.45	0.42	0.0	20.5
5	55	0.73	0.34	24.2	0.0
6	32	0.56	0.24	0.0	47.0
7	85	0.25	0.60	1.3	0.0
8	72	0.43	0.37	0.0	0.0
9	36	0.50	0.36	0.0	73.0
10	53	0.55	0.36	5.8	5.0
11	87	0.34	0.49	18.6	0.0
12	89	0.33	0.50	19.2	0.0

Test 11: A list of operating parameter values used in the Box-Behnken test program conducted to optimize the classification performance of the Krebs Cyclowash

Operating Parameter Values				
Test#	Feed Pressure	Vortex Finder	Cone Diameter	Water Flow Rate
	(kPA)	(cms)	(cms)	(lpm)
1	162	5.08	3.81	0
2	131	5.08	3.81	75
3	100	6.35	3.81	75
4	131	5.08	3.81	75
5	131	5.08	5.08	0
6	162	6.35	3.81	75
7	131	6.35	3.81	0
8	131	3.81	3.81	150
9	162	3.81	3.81	75
10	131	5.08	2.54	150
11	131	5.08	2.54	0
12	131	5.08	3.81	75
13	131	6.35	3.81	150
14	100	3.81	3.81	75
15	131	5.08	5.08	150
16	131	3.81	3.81	0
17	131	3.81	2.54	75
18	162	5.08	5.08	75
19	131	5.08	3.81	75
20	131	3.81	5.08	75
21	162	5.08	2.54	75
22	131	6.35	5.08	75
23	100	5.08	3.81	150
24	131	5.08	3.81	75
25	100	5.08	2.54	75
26	100	5.08	5.08	75
27	131	6.35	2.54	75
28	162	5.08	3.81	150
29	100	5.08	3.81	0

Table 12: The classification performance data obtained from the Box-Behnken experimental program conducted to optimize Cyclowash performance.

Test#	d50c	d95c	Imperfection	Selectivity	Oversize Bypass	Undersize Bypass
	(micron)	(micron)		Index	(% Weight)	(% Weight)
1	39	110	0.47	0.38	0	19.4
2	51	116	0.48	0.40	0	10.0
3	74	119	0.37	0.45	16.6	0.7
4	56	118	0.46	0.41	0	8.7
5	42	107	0.38	0.45	0	29.3
6	65	119	0.42	0.42	14.1	0.0
7	52	116	0.46	0.43	9.6	4.9
8	46	113	0.40	0.46	0	11.0
9	39	107	0.45	0.39	0	31.3
10	88	121	0.22	0.64	0	0.0
11	77	120	0.32	0.51	0	4.7
12	54	117	0.51	0.36	0	9.3
13	70	119	0.41	0.40	12.2	0.0
14	41	113	0.53	0.35	0	22.8
15	48	115	0.56	0.31	0	12.7
16	36	102	0.44	0.40	0	47.7
17	53	117	0.49	0.39	0	10.7
18	44	113	0.47	0.39	0	15.0
19	52	117	0.53	0.35	0	7.9
20	40	105	0.41	0.42	0	25.9
21	76	120	0.34	0.49	0	2.6
22	62	118	0.48	0.37	8.0	6.0
23	85	121	0.25	0.60	10.9	0.0
24	47	115	0.53	0.35	0	12.3
25	79	120	0.31	0.52	3.3	2.6
26	52	116	0.44	0.44	7.9	10.9
27	63	118	0.44	0.41	0	0.0
28	65	119	0.42	0.42	4.1	0.5
29	45	114	0.52	0.36	1.8	26.2