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Project Summary

Evaluation of Low Gravity Dense Media Cyclone Performance in Cleaning Fine Coal

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Thirty-six pilot plant tests were conducted to evaluate the performance of dense medium cyclones in cleaning fine coal (9x100 mesh)* at a low specific gravity of separation (1.3). (NOTE: These cyclones, consisting of finely ground magnetite and water, are commonly used in the coal industry to separate coal and mineral particles.) Test variables included two orifice sizes, three medium-to-coal weight ratios, and six flow rates. The clean coal (overflow) and refuse (underflow) from these tests were separated into three size fractions (9x14, 14x28, and 28x100 mesh) and float/sink tested at eight specific gravities. This report gives results of statistical analyses which were performed to evaluate these tests. Performance criteria used in these evaluations included: four dependent criteria (recovery efficiency, misplaced material, yield error, and ash error); three independent criteria (probable error, error area, and imperfection); and three sulfur-based criteria (percent sulfur in coal, percent sulfur reduction, and percent reduction in pounds per million Btu). Final results of the statistical analysis were regression equations relating each performance criterion to particle size, orifice size, flow rate, and medium-to-coal ratio. Particle size was statistically related to cyclone performance for all criteria examined, except weight recovery, efficiency, and percent reduction in pounds per million Btu. Generally, the best performance occurred at the 9x14 mesh size range and deteriorated as particle size decreased. Cyclone performance improved with increasing flow rate up to 120 gpm, then decreased beyond this value. Cyclone performance, as measured by the dependent criteria, improved slightly when a 1.5 in. orifice was used. Percent coal in slurry was a statistically significant predictor of all measures of performance criteria, except weight recovery efficiency. In general, best performance occurred at a nominal medium-to-coal ratio of 7:1 and deteriorated as the percentage of coal in the slurry increased. The cyclone operating parameters were, in general, more highly correlated with the independent measures of cyclone performance than with dependent or sulfur-based criteria.

This Project Summary was developed by EPA's Industrial Environmental Research Laboratory, Research Triangle Park, NC, to announce key findings of the research project that is fully documented in a separate report of the same title (see Project Report ordering information at back).

*Readers more familiar with metric units may use the conversion figures at the back of this Summary.

Introduction

The Multi-stream Coal Cleaning Strategy (MCCS) is being tested by the Pennsylvania Electric Company (PENELEC) and the New York State Electric & Gas Corporation (NYSEG) to control emissions of sulfur oxides from coal-fired boilers at the Homer City, PA, Generating Station. The MCCS is based on physical coal cleaning using dense medium cyclones in which mineral impurities, including pyritic sulfur, are removed from raw coal. Dense medium cyclones are used because they are very efficient in separating organic coal particles from the more dense mineral particles. The apparent density of the medium is controlled by mixing finely ground magnetite with water.

In a dense medium cyclone, centrifugal force is used to separate particles of different specific gravities. The specific gravity (s.g.) of organic coal particles may range from 1.3 to 1.9, while that of coal mineral particles may range from 2.2 to 5.0. To remove most of the mineral contaminants from coal it is necessary to crush the raw coal to fine particle sizes and separate these particles at a low specific gravity. Prior to this project there was little data on the performance of dense medium cyclones operating on fine size coal particles at low specific gravity.

To provide additional data on dense medium cyclone performance a cooperative pilot plant test program was conducted by the Department of Energy (DOE), the U.S. Environmental Protection Agency (EPA), and PENELEC. Thirty-six tests were conducted at DOE's dense medium pilot plant at the Pittsburgh Energy Technology Center (PETC). These tests are documented in DOE/PECTC/TR-83/1 (DE83009250), Dense-Medium Cycloning of Fine Coal at Low Specific Gravities.

All of the dense medium tests were run with an 8-in. diameter dense medium cyclone operated at a nominal 1.3 s.g. with 9x100 mesh coal. The operating variables included two orifice sizes (1-1/2 and 1-3/4 in.); three medium-to-coal ratios (7:1, 5:1, and 3:1) and six flow rates (92, 100, 110, 120, 140, and 160 gpm). The overflow (clean coal) and underflow (refuse) from each test were divided into the three size fractions (9x14, 14x28, and 28x100 mesh) and float/sink tested at eight specific gravities. Each size and specific gravity increment was analyzed for moisture, ash, and total sulfur.

Bituminous Coal Research Inc. (BCR) was awarded a contract to perform statistical evaluations of the 36 dense medium pilot plant tests. Performance criteria used in these evaluations included: four dependent criteria (recovery efficiency, misplaced material, yield error, and ash error); three independent criteria (probable error, error area, and imperfection); and three sulfur-based criteria (percent sulfur in coal, percent sulfur reduction, and normalized percent sulfur reduction in pounds per million Btu).

This report documents the results of these statistical analyses.

Conclusions, Limitations, and Recommendations

The mathematical and statistical evaluations of dense medium cyclones conducted during this project have yielded several important conclusions regarding the relationships between cyclone operating parameters and the various performance criteria examined. These conclusions are presented and discussed in this section. In order that they may serve as operating guidelines, all conclusions are stated in terms of the relationship of the operating parameters to measured cyclone performance. Limitations of the stated conclusions are discussed, and recommendations are made for further work in evaluating cyclone performance.

Conclusions

Dense medium cyclone performance improves as particle size of the feed coal increases. Particle size was statistically related to cyclone performance for all criteria examined, except weight recovery efficiency and normalized percent sulfur reduction. Generally, best performance occurred for the 9x14 mesh size range and deteriorated as particle size decreased. Only for percent sulfur reduction was this tendency reversed; i.e., slightly higher percent reductions occurred as particle size decreased. When percent sulfur reduction was normalized for Btu value, this particle size effect was not observed.

Cyclone performance, as measured by the dependent criteria and percent sulfur reduction, was statistically related to flow rate. Flow rate is a statistically significant predictor of cyclone performance as measured by the four dependent criteria and percent sulfur reduction. In all cases, this relationship is best characterized using a second-order polynomial expression for flow rate, because cyclone performance improved with increasing flow rate up to a value of 120 gpm, then deteriorated as the flow rate increased beyond this value. Based on the flow-rate levels examined in the test matrix and the statistical models derived in this investigation, 120 gpm appears to produce overall best results for the criteria mentioned above. It is possible, however, that the true optimal flow rate is slightly higher or lower than 120 gpm.

Cyclone performance, as measured by the dependent criteria, was related to the size of the inlet orifice. In all cases, performance improved slightly when a 1.5-in. orifice was used.

Dense medium cyclone performance improved as the percent coal in slurry decreased. Percent coal in slurry was a statistically significant predictor of all measures of cyclone performance criteria examined, except weight recovery efficiency. In general, best performance occurred at a nominal medium-to-coal ratio of 7:1 and deteriorated as the percentage of coal in slurry increased. This tendency was most pronounced for independent measures of cyclone performance.

The cyclone operating parameters investigated are, in general, more highly correlated with independent measures of cyclone performance than with dependent or sulfur-based criteria. A comparison of the results obtained for the various performance criteria reveals that most of the variability (over 80 percent) in the independent measures can be accounted for through a knowledge of the operating parameters being considered. In contrast, among the dependent and sulfur-based measures, variability explained by the operating parameters generally ranges from about 25 to 70 percent. For sulfur in clean coal, less than 10 percent of the variability is explained; however, this is a poor measure of sulfur performance.

These results are not surprising when one considers that error area, probable error, and imperfection are essentially independent of the washability characteristics of raw coal. As such, these criteria are more characteristic of the performance of the coal-cleaning unit itself. However, some important and consistent relationships between operating parameters and dependent criteria have emerged from this evaluation. The observed correlations between cyclone operating parameters and the performance measures do indicate particular operating conditions under which cyclone performance is likely to be improved.

For the test matrix under investigation, cyclone operating conditions corresponding to Test No. 84 appear to produce best overall cyclone performance. The results of all statistical analyses performed in this investigation suggest that one area of the test matrix is optimal or very near optimal for all cyclone performance criteria examined. The operating conditions of Test No. 84 (i.e., 1.5-in. orifice size, 120 gpm flow rate, and 7:1 medium-to-coal ratio) seem to produce improved cyclone performance as compared to other cyclone operating configurations. While true optimal performance may not occur exactly at the conditions of Test No. 84, generally this is the best set of operating conditions in the test matrix under consideration.

Limitations

The results and conclusions of this evaluation are strictly applicable to 8-in. cyclones. Generalizations of these results to larger or smaller cyclones should be made with caution. Values of specific operating parameters used in this investigation, such as inlet-orifice sizes and flow rates, may not be appropriate for larger or smaller cyclones.

Extrapolations and interpolations of the relationships and prediction equations derived in this evaluation should be made with caution. The results of this analysis do not necessarily apply beyond the ranges of values for the operating variables that were used in this investigation. Further, interpolation of these results is limited by the number of levels of each operating parameter actually incorporated in the test matrix, particularly inlet-orifice size (which had only two possible values).

The results and conclusions of this evaluation, pertaining to dependent and sulfur-based criteria, are not necessarily generalized to other coals with different washability characteristics. The independent performance criteria, however, should apply to other coals.

The actual performance curves and performance criteria derived from these curves may be somewhat different from those derived using other curve fitting procedures; e.g., hand-drawn or other curve fitting routines.

Recommendations

Verification of the relationships and prediction equations derived from this analysis, carried out through additional cyclone testing, would be valuable. These tests could include other levels of the operating parameters, such as additional flow rates and inlet-orifice sizes. Examination of additional cyclone operating parameters, through matrix testing, would also be valuable. Emphasis could be on improving correlations for the dependent performance criteria; in particular, the sulfur-based measurers.

Extending results of the present investigation to larger cyclones, as well as verifying results for other coals, would also be of value.

Test Conditions

Thirty-six tests, using an 8-in. dense medium cyclone, were conducted at DOE's pilot plant in Bruceton, PA. The tests provided performance data for the cyclone operating under various conditions on coal particle mesh sizes of 9x14, 14x28, 28x100, and 9x100. The operating variables investigated included two inlet orifice sizes (1-1/2 and 1-3/4 in.); three medium-to-coal ratios (7:1, 5:1, and 3:1); and six flow rates (92, 100, 110, 120, 140, and 160 gpm). Operating conditions for each dense medium cyclone test are given in Table 1.

Test Equipment and Procedures

The pilot plant circuit contained an 8-in. diameter Heyl & Patterson cyclone with a 14° included angle, a full-stream slurry sampler, a 3-x2-in. centrifugal pump with a variable speed drive, a nuclear density gauge, a magnetic flowmeter, and a full-stream pressure sensor and gauge. A schematic of the dense medium pilot plant is shown in Figure 1.

The circuit was a closed-loop batch system that recirculated the slurry. Each test began with 60 gal. of water mixed with enough magnetite to produce the desired medium density, as indicated by the density gauge. The flow rate was set using a flowmeter and variable speed pump. The inlet pressure was read from the pressure sensor near the inlet. Once steady state was obtained, full-stream samples of the recirculating medium were taken to measure the medium distribution between the overflow and the underflow.

At this point, a measured weight of 9x10 mesh coal (100-200 lb), based on the recirculating medium density, was added to obtain the desired medium-to-coal ratio. The coal slurry was recirculated for only about 2 minutes, in order to minimize degradation while still allowing time for good mixing. Between 8 and 16 consecutive full-stream cuts through the product streams were then taken, depending on the flow rate and concentration. The sampler was designed to take identical simultaneous cuts of the clean coal (overflow) and refuse (underflow)

Table 1. *Dense Medium Cyclone Operating Conditions*

Test No.	Inlet Orifice in.	Inlet Pressure psi	Flow Rate gpm	Feed Coal tph	Medium-to-coal Ratio	Coal in Slurry, wt %
71	1.75	7.0	120	4.2	7:1	11.2
72	1.75	5.0	100	7.5	3:1	23.3
73	1.50	10.0	140	4.7	7:1	10.9
74	1.50	5.5	100	7.3	3:1	22.7
75	1.50	4.5	92	3.6	7:1	12.3
76	1.75	5.0	100	3.8	7:1	12.0
77	1.75	9.0	140	10.8	3:1	24.1
78	1.50	6.5	110	5.0	5:1	14.6
79	1.50	7.5	120	8.9	3:1	23.3
80	1.75	4.0	92	3.7	7:1	12.8
81	1.75	5.5	110	8.4	3:1	24.0
82	1.75	6.5	120	6.1	5:1	16.3
83	1.50	10.0	140	7.5	5:1	17.3
84	1.50	8.0	120	4.5	7:1	12.1
85	1.50	6.0	100	3.9	7:1	12.5
86	1.75	5.0	100	5.2	5:1	16.5
87	1.75	8.5	140	5.2	7:1	12.2
88	1.75	5.0	92	6.6	3:1	22.7
89	1.50	6.5	110	8.4	3:1	24.4
90	1.50	5.0	92	4.9	5:1	17.2
91	1.75	6.0	110	4.1	7:1	12.1
92	1.75	4.5	92	4.2	5:1	14.6
93	1.50	7.0	120	4.6	5:1	15.2
94	1.50	5.0	92	7.0	3:1	24.0
95	1.75	6.5	120	9.6	3:1	25.5
96	1.75	6.5	110	4.8	5:1	14.2
97	1.50	6.5	110	4.2	7:1	12.5
98	1.50	6.0	100	4.8	5:1	15.5
99	1.50	10.0	140	11.1	3:1	25.2
100	1.75	8.5	140	6.6	5:1	15.3
101	1.75	11.0	160	6.5	7:1	13.3
102	1.75	11.0	160	7.3	5:1	15.0
103	1.75	11.0	160	12.5	3:1	24.8
104	1.50	12.0	160	6.1	7:1	12.3
105	1.50	12.0	160	8.1	5:1	16.5
106	1.50	12.0	160	12.9	3:1	25.6

streams so that the yield could be based on the weights of the samples. About 10 lb of each product (clean coal and refuse solids) was necessary for subsequent washability analysis.

The weight and volume of slurry samples were measured, and the samples were wet-screened to remove magnetite. The products were dried and then checked with a hand-held magnet to remove any magnetite before the final weighing.

Each whole sample was screened into 9x14, 14x28, 28x100, and 100 mesh x 0 size fractions (Tyler screens). The three coarsest fractions were float/sink tested in organic heavy liquids at specific gravities of 1.27, 1.29, 1.32, 1.35, 1.40, 1.50, 1.60, and 1.80. Each float/sink increment was analyzed for moisture, ash, and total sulfur.

Performance Criteria

The cyclone performance criteria used in this statistical evaluation were dependent, independent, and sulfur based.

Dependent Criteria

Equipment performance criteria that depend on the properties of the coal being cleaned' are called dependent criteria. Four dependent criteria were used.

Recovery efficiency - the ratio, expressed in percentage, of the yield of cleaned coal to the yield of float coal of the same ash content shown, by specific gravity analysis, to be present in the feed.

Misplaced material - the sum of the sink material in the cleaned coal and the float material in the refuse, expressed as a percentage of the raw coal.

Yield error - the difference between the yield of coal actually obtained and the theoretical yield at the ash content of the cleaned coal.

Ash error - the numerical difference between the actual and theoretical ash content of cleaned coal at the yield of cleaned coal obtained.

Independent Criteria

Some equipment performance criteria are substantially independent of the coal properties. Independent performance criteria used in this study are determined from the separation distribution curve. The distribution curve is a plot of the percentage of each specific-gravity fraction of the coal feed recovered in the clean-coal product versus the median of the specific-gravity fraction. The specific gravity of separation is defined as the specific gravity of the material in the raw feed that is divided equally between clean coal and refuse. Three independent criteria were used.

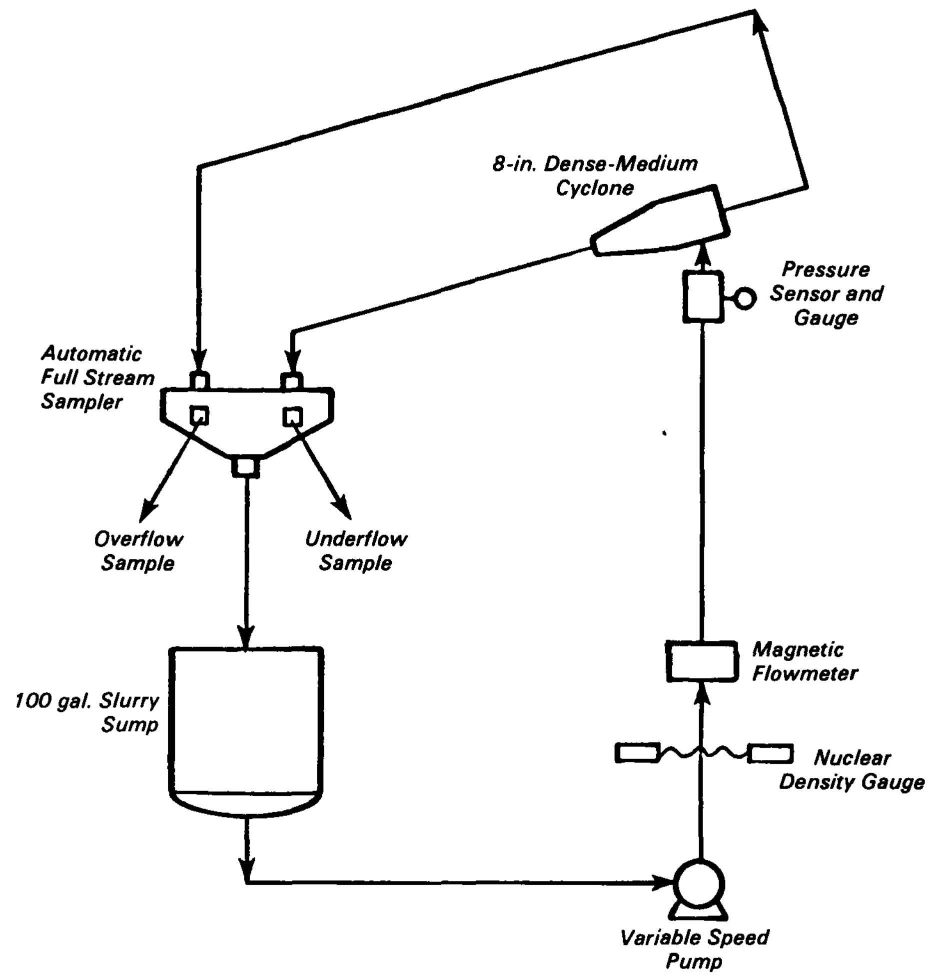

Figure 1. *DOE dense-medium cyclone pilot plant.*

Probable error - the slope of the distribution curve equal to half the specific gravity difference between the 25- and 75-percent ordinate values on the curve.

Error area - the area between the actual distribution curve and the theoretically perfect distribution curve. The theoretically perfect curve is a step function at the specific gravity of separation.

Imperfection - probable error divided by the specific gravity of separation.

Sulfur-Based Criteria

The performance of coal cleaning equipment in removing sulfur has not been traditionally evaluated. Sulfur based criteria are all dependent on coal properties. Three sulfur-based performance criteria were used.

Percent sulfur in clean coal - total sulfur content of clean coal determined from laboratory analysis.

Percent sulfur reduction - the difference between percent sulfur in feed and percent sulfur in clean coal, divided by the percent sulfur in feed.

Normalized percent sulfur reduction - computed using sulfur values for clean and feed coal expressed as pounds per million Btu. The Btu value of each specific gravity fraction was estimated from the ash content since the Btu value was not measured.

Analysis Methodology

Dense medium cyclone performance data for the 36 tests conducted at DOE's pilot plant in Bruceton, PA, were supplied to BCR by PENELEC. Computer software for data entry and verification was developed. Data files, created on a test-by-test basis, included all information provided by PENELEC (i.e., operating parameters and cyclone performance measures). Additional software was developed to generate long- and short-form data summaries for each test, as well as summary statistics (means and standard deviations) for any desired combination of tests.

Four distribution curves were generated for each cyclone test: one for each of the three particle-size ranges of coal and one for the composite size range. The technique used to fit curves to the distribution data is a mathematical procedure known as the cubic spline method. This curve fitting was accomplished using a computer program developed by BCR. One of the 108 computer generated distribution curves developed during the study is shown in Figure 2. The resulting smoothed distribution curves were evaluated by a second BCR computer program in order to compute values for the specific gravity of separation, probable error, error area, and imperfection. One of the 36 test data summary sheets developed during the study is given in Table 2.

Statistical analysis of the test data was performed to determine the effects of operating parameters on cyclone performance. Specifically, the objective of this analysis was to quantify the relationships between the operating variables under investigation (particle-size range, inlet-orifice size, flow rate, and medium-to-coal ratio) and the various cyclone performance criteria. The nature of these relationships suggests the most efficient set of operating conditions for each criterion. The statistical procedure used, known as multiple regression analysis, involved a general purpose computer program developed by BCR to perform multiple regression. Various functional forms of the operating parameters were examined in the course of the statistical analysis, as well as combination (or interactive) effects of these variables on cyclone performance.

All multiple function statistical analyses were conducted on a criterion-by-criterion basis. Stepwise regression models for predicting each criterion from the relevant cyclone operation conditions were developed. Relevant operating conditions, statistically related (at the 95-percent confidence level) to the given performance criterion, explained (accounted for) a significant portion of the observed variability in the criterion. The amount of explained variability was measured by the coefficient of multiple determination (MCC²). Specifically, the value MCC² (the

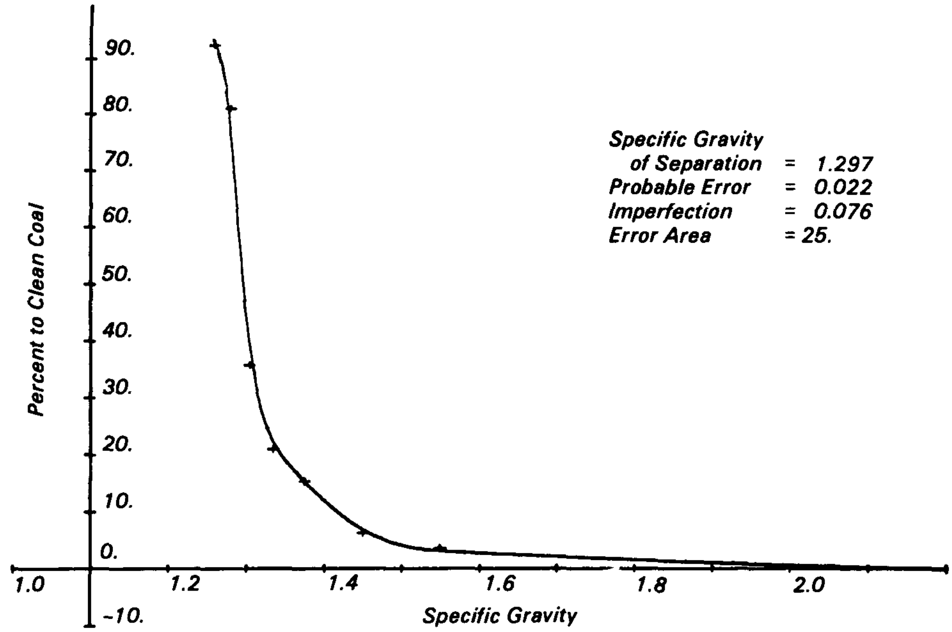

Figure 2. *Distribution curve, test No. 83 (9 x 100).*

Table 2. *Test 84 Data Summary*

	9x14	14x28	28x100	9x100
Screen Analysis, Percent:				
Feed	28.9	29.8	35.6	94.4
Clean Coal	19.1	30.5	43.3	92.9
Refuse	35.9	29.3	30.2	95.4
Ash, Percent:				
Feed	24.5	24.5	23.6	24.2
Clean Coal	2.8	3.4	3.7	3.4
Refuse	32.6	40.2	43.9	38.5
Total Sulfur, Percent:				
Feed	3.61	3.73	5.08	4.20
Clean Coal	1.11	1.16	0.90	1.03
Refuse	4.56	5.63	9.33	6.40
Weight Recovery (Yield)	27.4	42.6	50.4	40.9
Theoretical Weight Recovery	23.3	44.0	57.8	43.2
Weight Recovery Efficiency	100.0	96.8	87.3	94.7
Ash Error	0.0	0.1	0.7	0.2
Float in Refuse ...% of Product	9.2	16.1	22.7	15.9
Sink in Clean Coal	14.0	9.4	5.9	13.9
Total Misplaced Material ..% of Feed	10.5	13.2	14.2	15.1
Near Gravity Material	59.7	65.7	65.4	64.0
Specific Gravity of Separation	1.292	1.306	1.351	1.308
Probable Error	0.018	0.021	0.071	0.027
Imperfection	0.063	0.068	0.203	0.088
Error Area	11.	13.	40.	23.
Distribution, Percent to Cleaned Coal (Specific Gravity Fraction):				
Float 1.27	85.7	87.6	85.2	86.1
1.27-1.29	70.0	80.5	86.8	80.0
1.29-1.32	30.2	53.2	77.3	53.9
1.32-1.35	4.6	14.9	58.7	24.6
1.35-1.40	0.6	0.4	37.2	13.6
1.40-1.50	0.0	0.0	23.4	7.2
1.50-1.60	0.0	0.0	12.1	3.6
1.60-1.80	0.0	0.0	0.0	0.0
Sink 1.80	0.0	0.0	0.0	0.0

square of the correlation coefficient) represents the fraction of total variability in the given performance criterion that is accounted for by the regression model. The final prediction equation (regression model) was developed for each criterion, and comparisons were made between the predicted and observed values for each model. These values were used to indicate the overall fit of the regression model to the data as well as to select the set of cyclone operation conditions that would most likely produce the best results for the given performance criterion. Table 3 gives an example of the stepwise development of a regression model.

Results

General Statistical Properties

The mean values, standard deviations, and relative standard deviations for each performance criterion are given in Table 4. These statistical parameters are computed from test values in three size ranges for 36 tests (N=108). Data are also presented for the simple correlations between each criterion and each cyclone operating parameter.

The relative standard deviation (standard deviation ÷ MEAN) provides a relative measure of the variation in each performance criterion during the 36 tests. The weight recovery efficiency, percent sulfur in clean coal, percent sulfur reduction, and normalized percent sulfur reduction are not very sensitive to changes in the operating variables. The misplaced material and yield error show moderate sensitivity. The ash error, error area, probable error, and imperfection are the most sensitive.

The simple correlations provide an estimate of the strength and direction of the relationship between a performance criterion and single operating variable. The only operating variable which shows a strong correlation with the performance criteria is particle size. The large negative correlations for misplaced material, ash error, yield error, error area, probable error, and imperfection show that the value of these performance criteria increase significantly with decreasing particle size.

Table 3. Results of Regression Analysis for Yield Error

Step	Independent Variable	MCC	MCC^2	F-ratio
1	P	0.496	0.246	34.51*
2	F,F^2	0.639	0.408	28.49*
3	O	0.706	0.498	18.58*
4	R	0.722	0.522	5.01*

Final Prediction Equation

$$\hat{Y}_1 = -1.09\,F_1 + 0.004\,F_1^2 - 5.13\,P_1 + 12.56\,O_1 + 0.16\,R_1 + 58.27$$

MCC = 0.722
MCC^2 = 0.522
SEE = 3.58
O - Orifice size
F - Flow rate
R - Percent coal in slurry
P - Particle size
MCC - Multiple correlation coefficient
MCC^2 - Coefficient of multiple determination
F-ratio - Statistic for test of significance of regression model
** - Significant at 95-percent confidence level*
$\hat{Y}$ - Predicted value for criterion variable
SEE - Standard error of estimate

Statistical Evaluation of Dependent Performance Criteria

A preliminary examination of the correlations between the cyclone operating parameters and the dependent performance criteria indicated that all four operating parameters should be tested for inclusion in the final prediction models for the dependent criteria. First-order expressions for orifice size (O), percent coal in slurry (R), and particle size (P) were selected as potential predictor variables. A second-order polynomial expression was used in the case of flow rate (F,F^2).

The final models which were developed include those independent variables that are statistically significant at the 95-percent confidence level. The final models of three of the dependent performance criteria (misplaced material, ash error, and yield error) include all four independent variables (O, R, P, and F,F^2). Only O and F,F^2 are significant for weight recovery efficiency. The coefficients of multiple determination (MCC^2) for the final models range from 0.274 for weight recovery efficiency to 0.658 for ash error. Thus, these models are able to account for about 27.4 to 65.8 percent of the variability in the various dependent performance criteria. The final statistical models for the dependent, independent,

Table 4. Means, Standard Deviations, and Correlations for Cyclone Performance Criteria (N = 108)

Criterion	Mean	Standard Deviation	Relative Standard Deviation	Correlations: Orifice Size	Flow Rate	Percent Coal in Slurry	Particle Size
Weight Recovery Efficiency	77.96	8.22	0.11	-0.342	-0.108	-0.132	-0.008
Misplaced Material	14.62	3.75	0.26	0.201	-0.173	0.244	-0.615
Ash Error	1.14	0.73	0.64	0.222	0.103	0.240	-0.649
Yield Error	11.44	5.18	0.45	0.301	0.102	0.161	-0.496
Error Area	32.71	22.81	0.70	0.091	-0.036	0.176	-0.826
Probable Error	0.042	0.03	0.71	0.053	-0.043	0.233	-0.799
Imperfection	0.129	0.08	0.62	0.055	-0.049	0.203	-0.803
Percent Sulfur in Clean Coal	1.00	0.15	0.15	-0.002	0.019	0.196	-0.200
Percent Sulfur Reduction	68.50	9.30	0.14	0.059	-0.504	-0.215	-0.249
Normalized Percent Sulfur Reduction	75.65	7.90	0.10	0.065	-0.515	-0.223	-0.120

and sulfur based criteria are summarized in Table 5.

Statistical Evaluation of Independent Performance Criteria

Distribution curves were generated using the cubic spline method on a test-by-test basis. Four curves are drawn for each test: one for each particle-size range and one for the composite. Values for the three independent criteria, along with the specific gravity of separation, are reported for each curve. These values were read or computed from the distribution curve shown.

A preliminary examination of the correlation between the cyclone operating parameters and the independent performance criteria indicated two statistically significant parameters to be tested for inclusion in the final prediction models for the independent criteria. A second-order polynomial expression for particle size (P,P^2) and a first-order expression for percent coal in slurry (R) were selected as potential predictor variables.

Final models for all three independent performance criteria (error area, probable error, and imperfection) include both P,P^2 and R (see Table 5). The coefficients of multiple determination (MCC^2) for the final models range from 0.828 for imperfection to 0.881 for error area.

Statistical Evaluation of Sulfur-Based Performance Criteria

As for the dependent performance criteria, a preliminary examination of the correlations between the cyclone operating parameters and the sulfur-based performance criteria indicated that all four operating parameters should be tested for inclusion in the final models for sulfur-based criteria. First-order expressions for orifice size (O), percent coal in slurry (R), and particle size (P) were, again, selected as potential predictor variables. A second-order polynomial expression was used for flow rate (F,F^2).

The final model for sulfur in clean coal includes two significant terms, namely, P and R (see Table 5). For percent sulfur reduction, P and R are significant in the final model. For normalized percent sulfur reduction, F,F^2 and R are significant. The coefficient of multiple determination (MCC^2) is only 0.078 for percent sulfur in clean coal, as compared to 0.535 and 0.491 for percent sulfur reduction and normalized percent sulfur reduction, respectively. This large difference is due to variations in sulfur content in the feed coal. Percent sulfur in clean coal includes the variability in feed coal sulfur content, making it a less desirable measure of cyclone performance than either percent sulfur reduction or normalized percent sulfur reduction, both of which adjust for differences in the sulfur content of the feed. Normalizing percent sulfur reduction for Btu value had little effect on the magnitude of the overall correlation; however, it did remove the particle size effect (P) from the final model.

Metric Equivalents

EPA policy includes use of metric units in all its documents. Although this summary uses nonmetric units for convenience, readers more familiar with the metric system are asked to use the equivalents below:

Nonmetric	Multiplied by	Yields Metric
Btu	1055.06	J
gpm	3.785	l/min
in.	2.54	cm
lb	0.454	kg
lb/10^6 Btu	429.91	ng/J
psi	70.307	g/cm^2
tph	0.907	tonne/hr

Tyler Screen Size Mesh Openings

Mesh Size	*Sieve Opening* in.	mm
9	0.0787	2.00
14	0.0469	1.18
28	0.0234	0.60
100	0.0059	0.15
200	0.0029	0.075

Table 5. *Predicted Regression Equations for Various Performance Criteria*[a]

Performance Criterion $\hat{Y}_i$	Predicted Regression Equations	MCC	MCC^2	SEE
Weight Recovery Efficiency	$\hat{Y}_i = 1.71\ F_i - 0.007\ F_i^2 - 22.37\ O_i + 12.74$	**0.524**	**0.274**	7.01
Misplaced Material	$\hat{Y}_i = -0.53\ F_i + 0.002\ F_i^2 - 4.61\ P_i + 0.18\ R_i + 6.18\ O_i + 39.97$	**0.757**	**0.573**	2.45
Ash Error	$\hat{Y}_i = -0.14\ F_i + 0.0006\ F_i^2 - 0.95\ P_i + 0.03\ R_i + 1.32\ O_i + 7.52$	0.811	0.658	0.43
Yield Error	$\hat{Y}_i = -1.09\ F_i + 0.004\ F_i^2 - 5.13\ P_i + 12.56\ O_i + 58.27$	0.722	0.522	3.58
Error Area	$\hat{Y}_i = -0.0001\ P_i + 54.73\ P_i^2 + 0.78\ R_i + 95.70$	0.938	0.881	7.88
Probable Error	$\hat{Y}_i = -0.188\ P_i + 0.070\ P_i^2 + 0.0014\ R_i + -0.117$	0.921	0.849	0.012
Imperfection	$\hat{Y}_i = -0.488\ P_i + 0.179\ P_i^2 + 0.0032\ R_i + 0.331$	0.910	0.828	0.034
Percent Sulfur in Coal	$\hat{Y}_i = -0.06\ P_i + 0.006\ R_i + 0.95$	0.280	0.078	0.15
Percent Sulfur Reduction	$\hat{Y}_i = 2.02\ F_i - 0.009\ F_i^2 - 4.62\ P_i - 0.32\ R_i - 32.59$	0.731	0.535	6.34
Normalized Percent Sulfur Reduction	$\hat{Y}_i = 1.73\ F_i - 0.0075\ F_i^2 - 0.287\ R_i - 14.44$	0.701	0.491	5.63

[a]*Terms are defined in Table 3.*

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The complete report, entitled "Evaluation of Low Gravity Dense Media Cyclone Performance in Cleaning Fine Coal," (Order No. PB 84-122 936; Cost: $22.00, subject to change) will be available only from:
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