T-2848

# DEVELOPMENT OF A MATHEMATICAL MODEL OF A SPIRAL CLASSIFIER

by

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November, 1983

A thesis submitted to the Faculty and the Board of Trustees of the Colorado School of Mines in Partial fulfillment of the requirements for the degree of Master of Science in Metallurgical Engineering.

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# ABSTRACT

A series of experiments have been carried out on a small spiral classifier to study the effects of design variables (weir height and slope) and operating variables (feed flow rate, pulp density, and size distribution) on the performance of the classifier.

The analysis of the experimental data has led to the development of a mathematical model of a spiral classifier which consists of four basic equations that express the cut size (corrected d50), water split between overflow and sand, reduced-performance curve and the finest size fraction appearing in the sand product, in terms of the operating and design variables.

This study shows that a spiral classifier model can be developed based on concepts of d50 (corrected) and the reduced-performance curve as is done for the hydrocyclone classifier. A significant finding is that use of the finest size fraction in the coarse product is the most effective way to calculate the corrected performance curve for the spiral classifier.

A demonstration digital simulation of a closed grinding-classifying circuit has been conducted using a plug flow cumulative-basis first order kinetic model for the ball

mill and the spiral classifier model which was formulated by the author of the thesis. The results obtained were satisfactory within acceptable limits.

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# GLOSSARY

| | |
|---|---|
| Ball Mill Hold Up, BMH | Ball mill volume occupied by pulp,m , or slurry weight in ball mill, ton. |
| Mean Residence Time, | Time the pulp remains in ball mill given by BMH/pulp volumetric flow rate or BMH/pulp mass flow rate |
| Breakage Function, Bij | A probabilistic function which expresses in fractional form the weight finer than screen number i after primary breakage of particles of screen number j. |
| Primary Breakage | A single event of breakage |
| Breakage rate, Ki | or cumulative specific rate-of-breakag,-rate of disappearance by breakage of a mass fraction of particles coarser than a given i, $min^{-1}$. |
| Actual Efficiency | or selective index, Y, the mass fraction of solids of a given particle size in the feed reporting to the sand (spiral classifier) or underflow (hydrocyclone classifier) |
| Performance-Curve | or selectivity curve, - a plot of Ea (Ec) against particle size. |
| Cut Size d50 | Particle size which represents particles with equal (50%) probability of reporting to either overflow or sand. |
| Water Split, Rf | the mass fraction of classifier feed water reporting to the overflow or sand (underflow). |

Corrected Efficiency, Ec -or classification index- the mass fraction of a given particle size in the feed reporting to the sand only because of classification.

Corrected-Performance Curve -or classification curve- a plot of Ec against particle size.

Reduced-Performance Curve
A plot of Ec against d/d50c.

Corrected Cut Size, d50c
The particle size at which Ec = 50%.

Sharpness of Separation, m
A fitted parameter to an assumed form of the classification curve, namely

$$Ec = 1 - \exp(-0.693(d/d50c)^{m})$$

m represents the slope (or 'steepness') of the curve, d is particle size.

## ACKNOWLEDGMENTS

The author is pleased to express his immense appreciation to the following:

Dr. D.J. Spottiswood for his encouragement, guidance and assistance during this work;

Dr. W.R. Bull and Dr. J. Hager for their encouragement and help;

Dr. S.F. Hui (Stephen) and the Colorado School of Mines for providing a Fellowship to me;

Prof. Hu Weibai of the Central-South Institute of Mining and Metallurgy (China) for his encouragement;

All faculty and graduate students in the Department of Metallurgical Engineering for their assistance, advice and friendship, particularly my good friends, Dr. R. Sen, Javier Ramirez and Jay Pillai;

All my dear Chinese friends who are studying in CSM for their assistance and encouragement;

And, finally, all the Chinese colleagues in my teaching group and my wife Liu Jinhua for their sharing my own work during the time I studied at the Colorado School of Mines, without which I would not have been able to complete this work.

# CHAPTER I

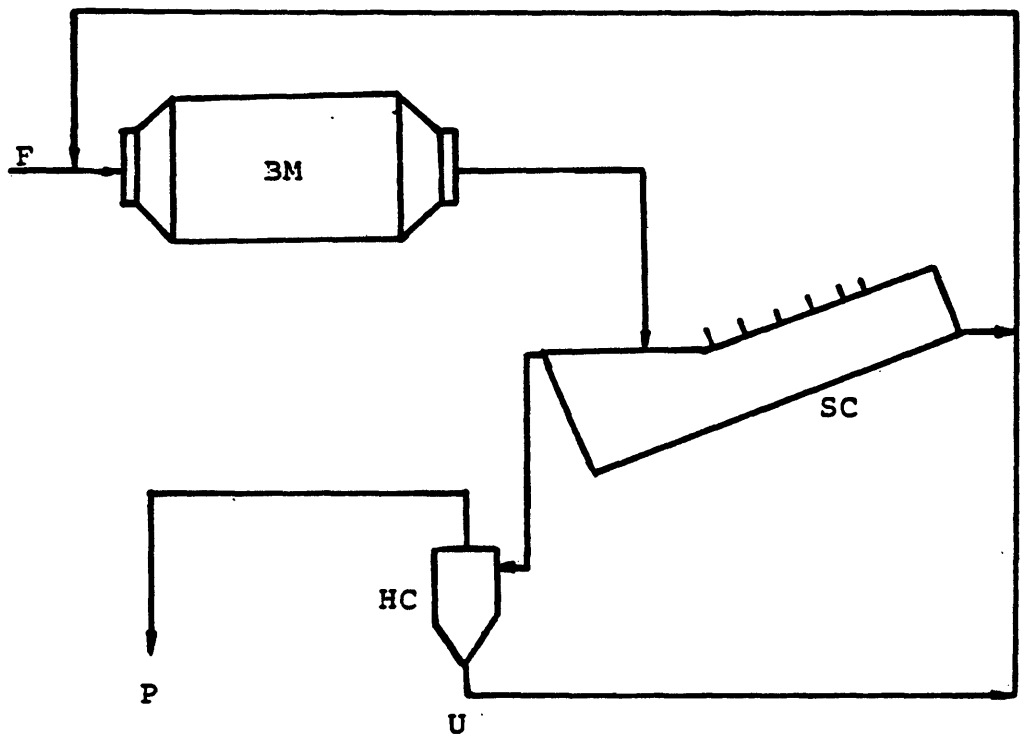
## INTRODUCTION

The objective of grinding in tumbling mills, as practised in mineral processing operations, is to produce a feed material for subsequent concentration steps such as flotation, magnetic separation, or gravity separation, which is sufficiently fine to have achieved good liberation of valuable mineral species from gangue but without producing excessive amounts of slime. In many respects, grinding is the most important unit operation in a mineral processing plant. If adequate liberation is not achieved during grinding, subsequent separation steps will yield low metallurgical recoveries and /or concentrate grades. Grinding energy requirements and operating costs typically exceed 50% of the total expenditures of the entire plant. Because grinding is an inherently energy intensive process and grinding circuit capital and operating costs are high, it is essential that such circuits be run as efficiently as possible. Increased efficiency in grinding usually translates to a decrease in the energy required per/ton to produce product size material.

A grinding circuit commonly consists of a ball mill and a classifier (or several classifiers). The efficiency of a grinding circuit is high, if and only if the efficiencies of both ball mill and classifier are high. It is generally accepted in the mineral industry that efficient grinding circuit performance can not be achieved without the use of some form of automatic control because all circuits are subjected to random disturbances. And it is also accepted in the mineral industry that the simulation of circuit operation by the use of mathematical models is useful in developing and evaluating possible control schemes. As a result, many mathematical models have been developed to meet the needs of process simulation and process control.

With respect to classification, the hydrocyclone has become the most important classification device because of its high capacity, mechanical simplicity, low capital cost and small space requirements. A variety of mathematical models have been presented to describe the hydrocyclone classifier performance. Because of their decreasing importance, other classifiers, including the spiral classifier, have recieved less attention, with the result that they are even less well understood. The spiral classifier, however, is still widely used in Chinese concentrators, and there are a significant number of installations in other parts of the world. While a spiral classifier can be used alone, in normal Chinese practice the spiral classifier is adopted for coarse-size material classification, and the hydrocyclone classifier is employed for fine-size material classification. Some of the typical closed wet grinding circuits are illustrated in Figure 1.1, and Figure 1.2.

The objective of the study is to experimentally develop a mathematical model of the spiral classifier, and to examine its application and suitability in the simulation of grinding-classifying circuits.

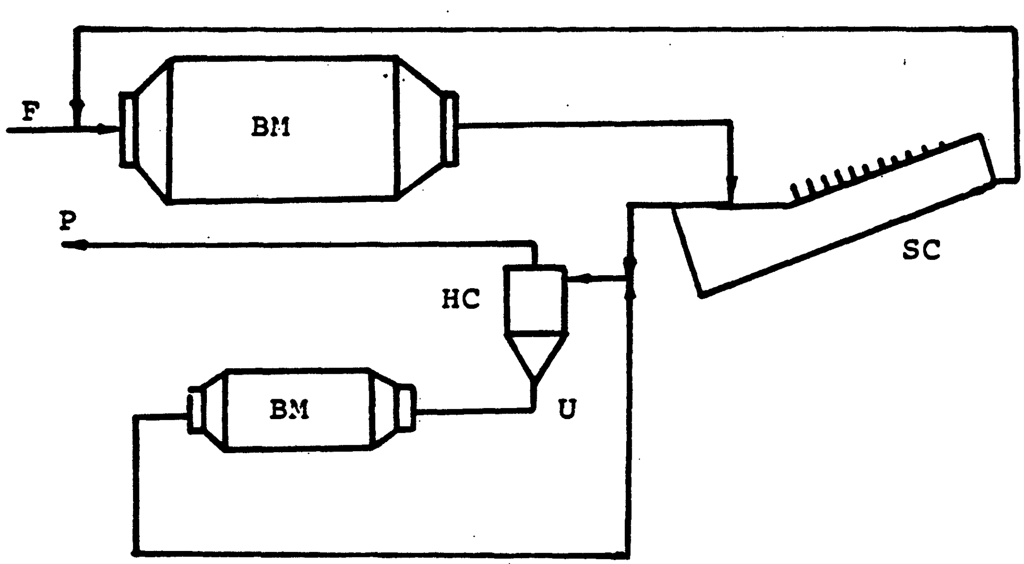



F feed P product

U underflow BM ball mill

HC hydrocyclone SC spiral classifier

Figure 1.1 One Stage Grinding and Two Stage Classifying Closed Grinding Circuit




F feed P product

U underflow BM ball mill

HC hydrocyclone SC spiral classifier

Figure 1.2 Two Stage Grinding and Two Stage Classifying Closed Grinding Circuit

# CHAPTER II

# LITERATURE REVIEW

Classification is the separation of particles according to their settling rate in a fluid. The fluid most commonly used in mineral processing is water. The major factors which affect the classification process are: the physical properties of the particle, such as size, shape, and specific gravity; the physical properties of the fluid, such as density, viscosity, solids content; and the design and operating variables of the equipment in which the separation is carried out.

The types of classifiers widely used in the mineral processing industry are mechanical (spiral and rake classifier) and centrifugal (hydrocyclone classifier). No universally acceptable theory so far exists for the classifier. Thus this chapter reviews a number of approaches which have been published. Although centrifugal and mechanical classifiers are different kinds of classifiers, they still have common principles of classification, and common methods of measuring classifier performance. For instance, in order to estimate classifier performance, performance (efficiency) curves, water flow ratio, and classification size (corrected d50) are used in both centrifugal and mechanical classifiers. Most operating classifiers have a characteristic S-shape performance curves (9), and similar mathematical models can be used to evaluate gravity-type classifiers (spiral and rake classifiers) and centrifugal classifiers (hydrocyclone classifier) (10).

Hence, before reviewing the spiral classifier, it is necessary to consider the hydrocyclone classifier.

## 2.1 Hydrocyclone Classifier Models

Over the past 30 years, the use of the hydrocyclone has become the accepted standard method of classifying slurries in the mineral processing industry. A lot of research work has been carried out on hydrocyclones, but with only limited success.

The performance of a hydrocyclone is affected by its dimensions and operating conditions. In order to develop correlations which include all of the essential variables, some methods of representing the performance are needed. In 1949, Dahlstrom (62) first used the d50 value of an operation to represent the solid elimination efficiency of the hydrocyclone. Although d50 is a significant parameter, a single-valued parameter is not an adequate description of the classification process. A more logical approach is to plot a performance curve to present the performance of a hydrocyclone operation. In 1953, Kelsall (11) explained the reason why the actual performance curve does not pass through the origin. Yoshioka and Hotta (12) suggested the idea of a "reduced efficiency curve" in 1955. This curve is obtained by plotting "centrifugal efficiency" or corrected mass percentage of particles reporting to the underflow against the actual size divided by the corrected d50. In 1964, Bradley (13) advanced eight different equations to calculate the cut size (d50) of a hydrocyclone and nine different equations to calculate the pressure. Most research work had been carried out with dilute slurries using small-diameter hydrocyclones, so that much of this work was not directly applicable to industry-scale hydrocyclones.

The most notable research on hydrocyclones has been carried out by Lynch and Rao (14) in the past 20 years. In their work, they formulated an empirical model which would describe the operation of large-diameter hydrocyclones under conditions of high solids contents, and used this model successfully for the analysis of hydrocyclone operation and in the simulation and automatic control of a closed grinding circuit at Mount Isa Mines (15). This is a simple empirical model which is based on concepts of d50 (corrected) and the reduced-efficiency curve. The model which Lynch and Rao have developed requires the determination of constants which must be experimentally evaluated for every application and which usually apply only to a relatively narrow range of operating conditions.

Plitt (7) has formulated a model which would give reasonable predictions over a wide range of operating conditions. His model consists of four basic equations which express the cut size (d50), volumetric split between overflow and underflow, volumetric throughput, and sharpness of separation in terms of the operating and design variables. Because of its broad data base and the inclusion of all major variables, the model may be used without experimental data to predict the operation of hydrocyclones over a wide range of operating conditions.

### 2.1.1 Hydrocyclone Performance Curves

The performance curve was introduced to the mineral processing industry by Tromp (63) in 1937. Although first used to describe the separation of coal on a density basis, this curve is also employed to represent a size-based solid-solid separation. The performance curve depicts the fractional recovery to the coarse product (underflow) of each individual particle size. The size-of-separation parameter is normally defined by the d50. The d50 represents the size at which the particles have equal probability of reporting to either the overflow (fine product) or underflow (coarse product).

Three types of performance curves are used, the actual, corrected and reduced for any one classification test. Typical performance curves for a hydrocyclone classifier are shown in Fig.2.1. Actual efficiency, Ea, at a point on the curve for a particular size material is given by:

$$Ea = Wu\ Mu/Wf\ Mf \qquad (2.1)$$

Where:

Ea = the fraction of particles of a particular size which is actually recovered in the underflow stream

Wu, Wf = mass fractions of the given size materials in the underflow and the feed stream, respectively

Mu, Mf = the mass flow rates of the underflow and the feed stream, respectively

Fine material is entrained by the coarse product liquid. This entrainment effect manifests itself as an

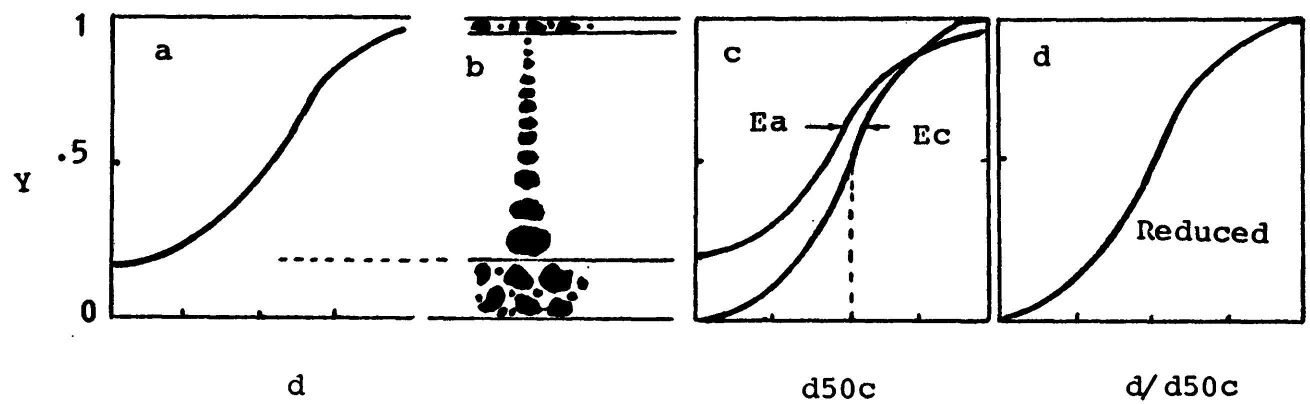



Figure 2.1 Classifier Performance Curve (9)

a — Characteristic form of a classifier performance Curve

b — Relationship of the performance to particle classification

c — The corrected performance curve

d — The reduced performance curve

Y — Weight fraction of feed to underflow intercept on the ordinate of the actual performance curve, recovered to the underflow, i.e., at fine sizes (as $d \to 0$), $Ea \to Rf$, the water split ratio. Therefore, separation due to classifying action, or corrected efficiency, Ec, is given by:

$$Ec = (Ea-Rf)/(1-Rf) \qquad (2.2)$$

Where:

Ec = the fraction of particles of a particular size which will be directed to the underflow discharge as a result of the classifying action

Rf = the fraction of feed liquid which is recovered in the underflow stream

The reduced efficiency curve is obtained by plotting corrected efficiency against the actual size divided by the corrected d50.

A number of equations have been developed to represent the entire reduced efficiency curve. The most commonly used are the two-parameter equations:

$$Ec = \{e^{\alpha x} - 1\}/\{e^{\alpha x} + e^{\alpha} - 2\} \qquad (2.3)$$

and

$$Ec = 1 - \exp(-0.693X^{m}) \qquad (2.4)$$

Where:

$X = d/d50c$

$\alpha$, m = empirical constants, both measures of the sharpness of separation and are approximately related as follows:

$$\alpha = 1.54m - 0.47 \qquad (2.5)$$

The reduced-performance curve is only used to determine the fundamental parameters of d50c and the sharpness of separation parameter m, or $\alpha$. In order to describe the actual performance curve, Eqs 2.2 and 2.4 can be combined as follows:

$$Ea = (1 - \exp(-0.693(d/d50c)^{m}) (1 - Rf) + Rf \quad .... (2.6)$$

Using equation 2.6 the solid separation action with respect to particle size can be represented with only three parameters: d50c, Rf, and m. With this eqation, the size distribution of both overflow and underflow can be predicted for a given feed.

### 2.1.2 The d50c Equation

Since d50c is the most important parameter for describing the performance of the hydrocyclone, attemps have been made to correlate it with operating and design variables. So far, a number of theoretical and empirical equations have been formulated to predict the d50c of a hydrocyclone.

Many of the theoretical equations use the equilibrium orbit hypothesis (13), that is, they balance the outward acting centrifugal force against the drag force due to the inward flowing liquid. One of the more rigorous equations is as follows (16):

$$d50 = 3(0.38)^n\{D_i^2/Kc\}\{ (\mu(1- R(+)L)\tan(\theta/2))/(DcIv(\rho s - \rho l))\}^{1/2} \quad \ldots. \quad (2.7)$$

Where:

R(+)L = mass fraction of feed liquid leaving through underflow

n = a parameter

Dc = inside diameter of hydrocyclone

Di = inside diameter of feed inlet

Iv = input volumetric flow rate

Kc = a parameter, dependent on design, fluid properties and Iv

$\theta$ = hydrocyclone cone angle

$\mu$ = viscosity

$\rho_s$ = solid density

$\rho_l$ = liquid density

Fahlstrom (17), proposed that the apex restricts the flow of solids, and that under the effect of centrifugal force the probability of a particle leaving through the apex is determined by its mass, so that the coarsest and heaviest particles discharge first and the discharge of the smaller and lighter particles becomes progressively more difficult. Thus:

$$R(+) = fn(Yu^{+}) \qquad (2.8)$$

Where Yu is a correlation for the size ditribution. For a Rosin-Rammler distribution:

$$Yu = \exp-(d/d^{*})^{s} \qquad (2.9)$$

and when equation 2.9 is substituted in Eq. 2.8 with d=d50c, results in:

$$d50 = d^*(-\ln R(+))^{1/s} \quad (2.10)$$

In Eq. 2.10, the d50 will be closer to the d50, a than the d50c, because of unclassified material which always appears in the underflow stream.

For empirical equations, the most extensive results have been presented by Lynch and Rao (14), and Plitt (7), who subjected their data to conventional regression techniques. The Lynch-Rao equation is:

$$\log(d50c) = K1VF-K2SPIG+K3Inlet+K4FPS-K5Q+K6 \quad .... \quad (2.11)$$

Where:

K1 to K5 = regression constants

VF = vortex finder diameter, cm

SPIG = spigot diameter, cm

Inlet = inlet diameter, cm

FPS = percent solids of pulp in hydrocyclone feed

Q = flow rate of pulp in the inlet, l/min

The regression constants K1 to K6 reported by Lynch were:

K1=0.0400 K4=0.0299

K2=-0.0576 K5=-0.00005

K3=0.0366 K6=0.0806

The Plitt equation is:

$$d50c = \frac{50.5\ Dc^{.45} Di^{.6} Do^{1.21}\ \mu^{.5} \exp(.063\phi)}{Du^{.71} h^{.38} Q^{.45}\ (\rho_s - \rho)^{.5}} \quad (2.12)$$

Where:

Dc = hydrocyclone diameter, cm

Di = inlet diameter, cm

DO = vortex finder diameter, cm

$\mu$ = suspending liquid viscosity, centipoise

$\phi$ = slurry volumetric solids content, % by volume

Du = apex diameter, cm

h = free vortex height, cm

Q = volumetric flow rate, l/min

$\rho_s$ = solid density, g/cm

$\rho$ = suspending liquid density

### 2.1.3 The Water Split Equation

The water split equation must be determined around a classifier in order to establish the underflow liquid recovery term, Rf, in equation 2.6. For hydrocyclones, Lynch (2) found that the equation was of the the form:

$$Rf = K1.SPIG/WF - K2/WF + K3 \qquad (2.13)$$

Where:

WF = the mass flow rate of water in the feed, t/h

K1 = 193, regression constant

K2 = 271.6, regression constant

K3 = -1.61, regression constant

Alternately an equation was developed by Plitt (7) to predict the volumetric split between overflow and underflow of hydrocyclones:

$$S = \frac{1.9(Du/Do)^{3.31} h^{.54} (Du^2+Do^2)^{.36} \exp(.0054\phi)}{H^{2.4}\ Dc^{1.11}} \qquad (2.14)$$

Where Du, Do, Dc and h are in cm; their meanings as described above

H = head in terms of meters of feed pulp

$\phi$ = solid percent by volume

S = {underflow volumetric flow rate}/
{overflow volumetric flow rate}

### 2.1.4 The Capacity Equation

The relationship between throughput and operating pressure in hydrocyclones is very important in the selection of the pump for the hydrocyclone installation. The regression equation developed by Lynch and Rao (2,14) to relate pressure and throughput for a hydrocyclone with constant feed size is:

$$Q = K\ VF^{.73}\ Inlet^{.86}\ P^{.42} \qquad (2.15)$$

Where:

Q = volumetric throughput, l/min

P = hydrocyclone feed pressure, Kpa

K = regression constant

## 2.2 Spiral Classifier Model

As mentioned in Chapter I, mechanical classifiers, including rake and spiral classifiers, have received less attention because they are used in fewer and fewer concentrators, particularly in the concentrators of Western countries. Although a thorough literature search was undertaken, a suitable model of a spiral classifier was not found. Taggart (18) pointed out that the capacity of the spiral classifiers is based on the outside diameter of the spiral, and gave some curves to show the relationship between the the capacity and the diameter of the spiral.

The U.S. Bureau of Mines carried out experiments on removing fines from coal using hydrocyclones in conjunction with the spiral classifier (19,29), with the objective of providing the maximum recovery of solids at minimum moisture content. Many variables which affect the performance of spiral classifiers were investigated, such as the influence of pool area, slope, influence of feed rate, influence of feed size, etc, but the experimental results were only given in tabulated or graphical form; the application of this these data is limited.

In a study of a small spiral classifier (21) the dynamic behavior of the classifier was investigated by residence time studies. The residence time of the particles was examined using both solid particles and dissolved sodium chloride as tracers in a manner similar to that employed for studies of the ball mill, (22), flotation cells, (23,24), and hydrocyclones(25). It was shown that there were four main zones in the active portion of the spiral classifier. These are shown diagrammatically in Fig.2.2. Zone A, the small, low pulp density portion of the pool above the classifier spiral, containing predominantly solids of overflow; zone B, the main body of the pool in which the spiral is rotating, and from which particles may eventually go either to the overflow or the sand; zone C, where

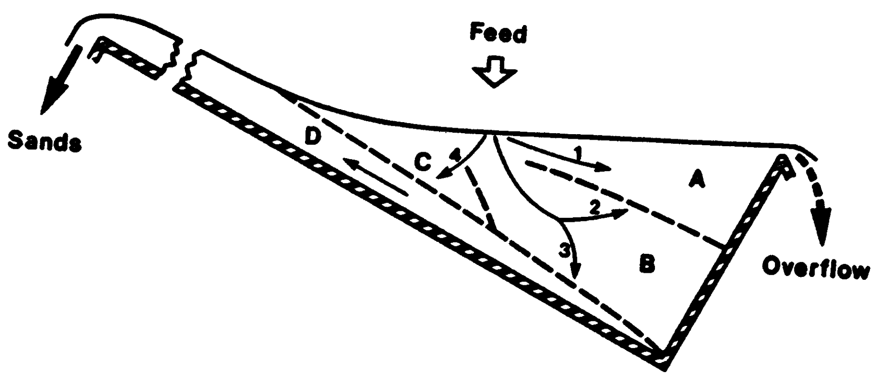



Figure 2.2 Major Zone in a Spiral Classifier(9)
and the Main Routes Taken by Solids

virtually all particles pass into the sands; and zone D, the region at the bottom of the classifier where the spiral conveys sands at high pulp density to the discharge. Thus, discharge can be considered to occur along four main routes. Overflow material leaves by routes 1 and 2. Via route 1, particles are carried through A almost directly to the overflow. Typically their residence time is 0.1— 0.3 of the average for all overflow particles, small particles having the higher value. Routes 2 and 3 pass through zone B — a large well mixed zone in which particles may enter zone A and leave via the overflow if they are fine enough (path 2); alternatively, independent of size, they may be conveyed by the spiral to the sands discharge (path 3). All particles passing along route 2 to the overflow have a similar residence time — about 1.6 times the average for all overflow particles. Route 3 carries the majority of particles leaving in the sands; the residence time decreases as the particles size increases (coarse particles with relatively high settling rates). Even so, these residence times are 4 — 6 times as long as those of particles which exit via route 4. The net residence time of all sands particles is further increased by spiral transportation time.

The dynamic behavior of the small spiral classifier was successfully analysed using this approach. Graphical analysis of test results suggested a simple physical representation of the movement of solid particles within the classifier which was simulated using an analogue computer. The results of this study have been used in a dynamic model of closed-circuit grinding (26).

Putman and Spottiswood (27) proposed a simple spiral classifier model which was adopted in closed circuit grinding. This model is based on the motor power of the spiral classifier, and the ore recyle rate from the classifier which is proportional to classifier motor power. Thus,

$$R = K1(P - K0) \qquad (2.16)$$

Where:

P = the classifier motor power

R = the ore recycle rate from the classifier

K0, K1 = constant

Because classifier motor power is not in fact merely linearly related to the recycle rate, they suggested another expression:

$$P = Ko + \{1/K1T\}\int_{-T}^{0} U dt \qquad (2.17)$$

Where:

U = the rate of recycled material entering the classifier at time t

T = the retention time of material in the classifier (assuming plug flow)

# CHAPTER III

# EXPERIMENTAL WORK

The experimental work entailed two principal efforts: to examine the influence of operating and design variables on classifier performance, and to develop a mathematical model of the spiral classifier.

## 3.1 Experimental Material

The test material for the experiments was dolomite $(Ca,Mg)CO_3$, in the size range of 25 — 35 mm. Before utilization, the dolomite was reduced in size using a jaw crusher , a cone crusher and a ball mill. The flowsheet for preparing the experimental feed material is shown in Fig.3.1, and the feed material size distribution is given in Table 3.1.

The specific gravity of the dolomite is 2.8. During the tests, sample 2 or sample 3 was added to sample 1 to change the feed size distribution.

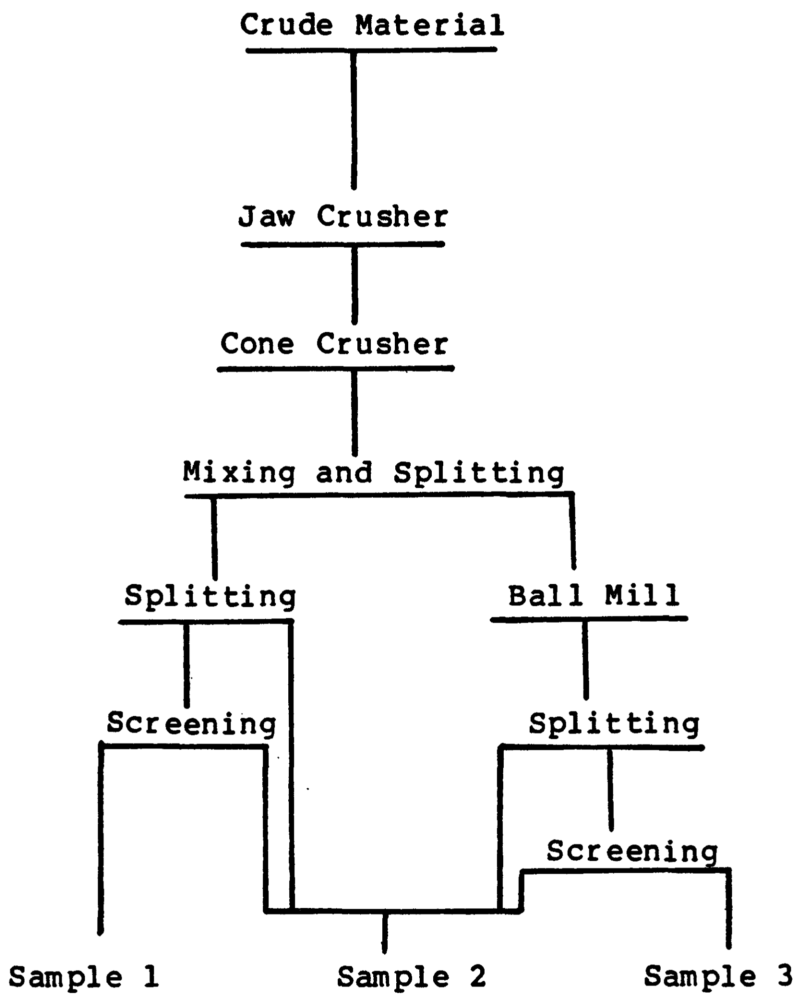


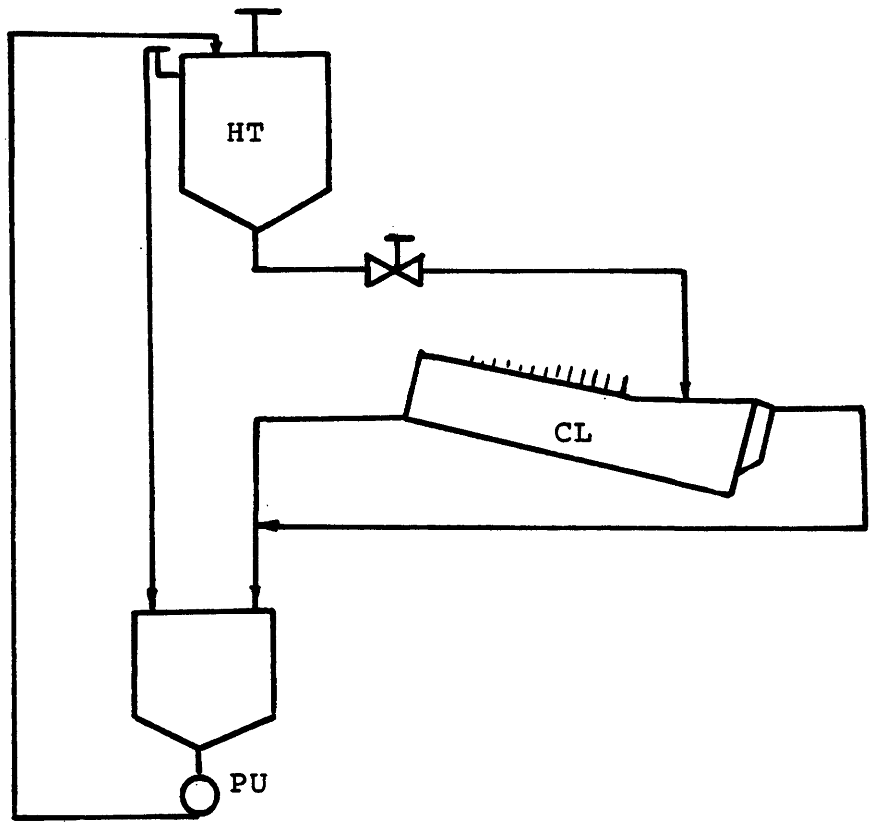

Figure 3.1 The Flowsheet for Preparing Experimental Material

Table 3.1 Size Distribution of Experimental Material

| Size (micron ) | Sample 1 | Sample 2 | Sample 3 |
|---|---|---|---|
| 2360 | 0.07 | 0.15 | 0.00 |
| 1180 | 7.10 | 9.00 | 5.20 |
| 475 | 25.26 | 43.48 | 7.03 |
| 300 | 8.27 | 6.31 | 10.22 |
| 212 | 8.71 | 8.34 | 9.08 |
| 150 | 8.33 | 7.24 | 9.43 |
| 75 | 6.51 | 5.35 | 7.66 |
| 53 | 10.68 | 6.31 | 15.06 |
| -53 | 25.07 | 13.82 | 36.32 |
| | 100.00 | 100.00 | 100.00 |

## 3.2 Experimental Apparatus

Fig.3.2 is a flowsheet of the test circuit. A small 220 X 1300 mm spiral classifier was employed in these tests. The spiral has a pitch of 100 mm and the speed of the spiral was held constant at 12 rpm. The slurry was pumped from a sump to an agitated head tank from which the slurry was fed by gravity to the spiral classifier. A by-pass line went from the head tank back into the sump; a valve at the head tank outlet was used to regulate the classifier feed rate.




HT head tank

PU pump

CL classifier

Figure 3.2 Simplified Flowsheet of Classifier Circuit tank outlet was used to regulate the classifier feed rate. Both the overflow product and the sands product of the classifier returned by gravity to the sump, thus closing the circuit.

### 3.3 Experimental Design

An experimental design is a very useful technique to minimize the experiments required to determine the functional relationship between response and operating variables, Y=f(X1,X2,....,Xn)+e for a process in the laboratory or the plant. 2 factorial designs have been proven to be useful for such studies(27). Most of the tests were organized on a framework of a two-level factorial design for this study.

#### 3.3.1 Selection of the Variables Affecting the Classification Process

According to the literature (9,30) and from experience, the major variables affecting the spiral classifier performance were selected as follows:

X1 -- volumetric flow rate in feed, l/min

X2 -- pulp density, %

X3 -- % +425 microns in feed

X4 -- % -53 microns in feed

X5 -- weir height, mm

X6 -- slope of classifier, degrees

Variable X4 was selected because the slime greatly effects the slurry viscosity and hence classifier performance(30,33).

3.3.2 Design Matrix for $2^6$ Factorial

A design matix for $2^n$ factorial had been introduced in detail (29) where n=1 to 5. Because six variables were selected in these experiments, a 2 factorial design matrix has to be used. However, a modified factorial design may be used; the design of the experiments is shown in Table 3.2 (31), where there are two levels of the factors, with the letters A, B, C, D, E, F representing the factors. In Table 3.2, columns 1, 2, 4, 8, 11, 13 represent major effects, columns 7 and 14 can be used to estimate experimental error, and the other colummns will show the interaction effects.

It is well known that regression techniques are greatly simplified when an orthogonal least squares procedure can be used. The operating variables of the spiral classifier, such as size distribution in feed, however, are usually difficult to control as a constant at two levels, hence the experimental data have been processed using stepwise regression and multiple regression techniques (34).

Table 3.2 Modified Experimental Design

| Col. | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Factor | | | | | | | | | | | | | | | |
| | A | B | AB | C | AC | BC | | D | AD | BD | E | CD | F | | CE |
| | | | DE | | DF | EF | | | BE | AE | | AF | | | |
| | | | | | | | | | CF | | | | | | |

## 3.4 Experimental Procedures

The experimental procedures were simple. Dolomite and water were added to the pump sump in the amounts needed to give the desired pulp density. When the circuit reached equilibrium, the samples of the sands and overflow product were collected simultaneously and tared in calibrated containers. In these tests, the mass, moisture content, and screen analysis were determined for each sample.

### 3.4.1 Sampling

The classification circuit would be considered in equilibrium when the following inequality was satisfied:

$$F-(O/F + S)/F < 0.05 \qquad (3.1)$$

Where:

F = slurry mass in feed

O/F = slurry mass in overflow

S = slurry mass in sands

As the circuit reached equilibrium, the volumetric flow rate and pulp density were checked to make sure that the operating variables are at the set values, then samples were taken. The reason for taking a feed sample was to establish the experimental error.

3.4.2 Screening

U.S. standard testing sieves were employed and screening was performed on a sieve shaker. In order to determine the optimum time for dry screening on the sieve shaker, a series of screening tests using dolomite as testing material were performed to check the accuracy of the screening analysis. To overcome the agglomeration problem arising when samples having high slime content were dry-screened, a combined wet-dry screening procedure was used (30,32). The following describes the screening sequence used:

a) Wet screening of material (about 200 g) on the finest screen (53 microns)

b) Decanting, then drying the coarse fraction at no more than 150°C

c) Dry screening the coarse fraction on the sieve shaker for 10 minutes

d) Weighing the coarse fractions

e) Calculating the size analysis

Note that the finest fraction (-53 microns) would be calculated according to the following equation:

$$W_{-53} = (a - W_{+53}) + b \qquad (3.2)$$

Where:

$W_{-53}$ = the mass of the particles less than 53 microns

$W_{+53}$ = the mass of the particles larger than 53 micron in wet screening

a = the mass of the sample in wet screening

b = the mass of particles less than 53 microns in dry screening

### 3.4.3 Duplicate Tests

Duplicate tests were conducted to establish the experimental error involved in the determination of the measured and calculated parameters. Table 3.3 shows the data for some of the repeated tests.

Table 3.3. Sample of Duplicate Test Data

| RUN | X1 | X2 | X3 | X4 | X5 | X6 | RF | FZ | d50c | m |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 10.10 | 42.10 | 23.35 | 33.80 | 135 | 10.9 | 10.59 | 7.41 | 126.27 | 1.10 |
| 2 | 11.27 | 40.33 | 22.41 | 35.43 | 135 | 10.9 | 8.43 | 7.10 | 115.24 | 1.15 |
| Av. | 10.68 | 41.22 | 22.88 | 34.62 | 135 | 10.9 | 9.51 | 7.26 | 120.76 | 1.13 |
| 14 | 14.93 | 53.23 | 12.75 | 38.84 | 135 | 13.0 | 2.42 | 5.46 | 1003.92 | 1.48 |
| 15 | 15.34 | 50.62 | 13.05 | 39.47 | 135 | 13.0 | 2.05 | 7.44 | 1009.03 | 1.52 |
| Av. | 15.14 | 51.93 | 12.90 | 39.16 | 135 | 13.0 | 2.24 | 6.42 | 1006.48 | 1.50 |
| 16 | 10.39 | 53.68 | 38.55 | 24.91 | 183 | 13.0 | 18.78 | 6.76 | 376.39 | 2.29 |
| 17 | 10.55 | 54.12 | 40.75 | 20.04 | 183 | 13.0 | 20.08 | 6.31 | 416.65 | 1.49 |
| Av. | 10.47 | 53.90 | 39.65 | 22.48 | 183 | 13.0 | 19.43 | 6.54 | 396.52 | 1.89 |
| 21 | 21.04 | 47.40 | 11.44 | 37.01 | 135 | 10.9 | 2.85 | 5.62 | 804.28 | 2.43 |
| 22 | 21.81 | 47.50 | 10.74 | 36.23 | 135 | 10.9 | 2.93 | 6.65 | 844.4 | 2.24 |
| Av. | 21.43 | 47.45 | 11.09 | 36.62 | 135 | 10.9 | 2.89 | 6.14 | 824.34 | 2.34 |

## 3.5 Summary of Test Conditions

A summary of the test conditions is given in Table 3.4.

## 3.6 Experimental Results

A total of 46 tests were conducted and for all tests carried out there was good agreement between the measured and calculated feed size analysis. Typical values are shown in Table 3.5.

The conditions of these tests given in Table 3.5 are actually the operating and machine variables which are considered independent variables. Rf, Fz, d50c, and the slope of reduced-performance curve, m, are dependent variables. Before giving the results of all tests the methods used for calculating the corrected efficiency, Ec, and cut size, d50c, will be described briefly.

### Corrected-Efficiency, Ec

In this study Ec was calculated using the following equation:

$$Ec = (Ea-Fz)/(1-Fz) \qquad (3.3)$$

Where:

Ea = actual efficiency

Table 3.4 Summary of Test Conditions

| Cond. No. | X1 l/min. | X2 % | X3 % | X4 % | X5 mm | X6 degree |
|---|---|---|---|---|---|---|
| 1 | 10.99 | 42.10 | 23.35 | 33.80 | 135 | 10.9 |
| 2 | 11.27 | 40.33 | 22.41 | 35.43 | 135 | 10.9 |
| 3 | 10.69 | 41.34 | 20.47 | 36.63 | 135 | 10.9 |
| 4 | 9.53 | 42.80 | 23.39 | 28.29 | 183 | 13.0 |
| 5 | 7.87 | 47.34 | 22.52 | 28.15 | 183 | 13.0 |
| 6 | 9.28 | 43.72 | 25.52 | 25.30 | 183 | 13.0 |
| 7 | 23.51 | 41.38 | 33.11 | 27.27 | 135 | 13.0 |
| 8 | 6.52 | 62.00 | 32.15 | 30.17 | 135 | 13.0 |
| 9 | 11.88 | 55.23 | 38.26 | 27.83 | 183 | 10.9 |
| 10 | 11.58 | 53.86 | 28.64 | 29.11 | 183 | 10.9 |
| 11 | 9.58 | 58.34 | 33.61 | 27.79 | 183 | 10.9 |
| 12 | 16.26 | 56.92 | 28.33 | 28.49 | 183 | 10.9 |
| 13 | 17.88 | 50.19 | 23.89 | 29.41 | 183 | 10.9 |
| 14 | 14.93 | 53.23 | 12.75 | 38.84 | 135 | 13.0 |
| 15 | 15.34 | 50.62 | 13.05 | 39.47 | 135 | 13.0 |
| 16 | 10.39 | 53.68 | 38.55 | 24.91 | 183 | 13.0 |
| 17 | 10.55 | 54.12 | 40.75 | 20.04 | 183 | 13.0 |
| 18 | 13.42 | 50.04 | 19.46 | 28.84 | 135 | 10.9 |
| 19 | 15.38 | 46.69 | 29.91 | 23.86 | 183 | 13.0 |
| 20 | 28.20 | 43.23 | 22.00 | 29.92 | 183 | 13.0 |
| 21 | 21.04 | 47.40 | 11.44 | 37.01 | 135 | 10.9 |
| 22 | 21.81 | 47.50 | 10.74 | 36.23 | 135 | 10.9 |
| 23 | 18.68 | 47.30 | 15.40 | 32.79 | 183 | 10.9 |
| 24 | 21.55 | 46.19 | 20.42 | 26.26 | 183 | 10.9 |
| 25 | 21.34 | 47.16 | 9.64 | 35.74 | 135 | 13.0 |
| 26 | 19.42 | 44.50 | 8.66 | 33.51 | 135 | 13.0 |
| 27 | 18.68 | 56.64 | 12.49 | 35.59 | 163 | 13.0 |
| 28 | 20.28 | 58.60 | 15.85 | 35.55 | 163 | 10.9 |
| 29 | 22.93 | 36.27 | 12.84 | 31.79 | 135 | 10.9 |
| 30 | 13.64 | 55.76 | 15.30 | 35.62 | 183 | 13.0 |
| 31 | 7.98 | 46.65 | 25.90 | 47.60 | 135 | 10.9 |
| 32 | 19.61 | 39.75 | 17.10 | 51.74 | 183 | 13.0 |
| 33 | 15.78 | 37.10 | 11.32 | 56.65 | 135 | 13.0 |
| 34 | 16.31 | 38.85 | 12.28 | 53.36 | 183 | 10.9 |
| 35 | 9.69 | 54.44 | 19.83 | 43.13 | 183 | 10.9 |
| 36 | 18.09 | 54.82 | 9.82 | 54.94 | 135 | 13.0 |
| 37 | 10.42 | 55.62 | 13.25 | 51.97 | 183 | 13.0 |
| 38 | 10.17 | 55.97 | 13.49 | 51.62 | 135 | 10.9 |
| 39 | 16.94 | 44.04 | 18.29 | 53.06 | 183 | 13.0 |
| 40 | 28.32 | 42.13 | 7.37 | 61.47 | 135 | 10.9 |
| 41 | 11.37 | 48.99 | 27.17 | 44.61 | 183 | 10.9 |
| 42 | 18.36 | 41.91 | 7.48 | 61.85 | 163 | 13.0 |
| 43 | 21.19 | 58.03 | 20.97 | 42.31 | 135 | 13.0 |
| 44 | 12.00 | 55.47 | 15.18 | 50.65 | 183 | 10.9 |
| 45 | 16.25 | 56.74 | 15.14 | 47.54 | 135 | 10.9 |
| 46 | 17.24 | 53.07 | 14.31 | 49.83 | 183 | 13.0 |

Table 3.5 Typical Feed Sizing Analyses

| Test No. | Size (microns) | Mass (%) Measured | Calculated |
|---|---|---|---|
| 9 | 2360 | 0.60 | 0.55 |
| | 475 | 38.10 | 37.71 |
| | 300 | 7.29 | 7.61 |
| | 212 | 6.60 | 6.32 |
| | 150 | 6.20 | 6.09 |
| | 75 | 2.72 | 2.34 |
| | 53 | 11.40 | 11.56 |
| | -53 | 27.35 | 27.83 |
| 17 | 2360 | 0.24 | 0.22 |
| | 475 | 40.27 | 40.53 |
| | 300 | 9.53 | 8.91 |
| | 212 | 7.91 | 7.41 |
| | 150 | 5.23 | 5.66 |
| | 75 | 12.98 | 12.91 |
| | 53 | 4.54 | 4.43 |
| | -53 | 19.30 | 20.04 |
| 19 | 2360 | 0.05 | 0.06 |
| | 475 | 29.94 | 29.85 |
| | 300 | 9.02 | 8.43 |
| | 212 | 7.69 | 8.00 |
| | 150 | 6.65 | 6.75 |
| | 75 | 11.24 | 11.97 |
| | 53 | 11.81 | 11.09 |
| | -53 | 23.60 | 23.86 |

Fz = %-53 microns in the sand

The reason for using Fz instead of Rf is discussed in detail in Chapter VI.

Cut Size d50c

There are four methods to calculate d50c from experimental data:

a) Liner Interpolation Method (i.e. straight line intercept method)

b) Lagrange Interpolation Method

c) Using the slope (index) of the reduced-performance curve, m, to calculate d50c

d) Direct from the reduced-performance curve

The comparision of d50c values calculated by each method, together with the calculation procedure and the computer program for calculation of the above three methods are given in Appendix III.

3.6.1 A summary of Experimental Results

Tables 3.6 shows the major results of all the tests.

In the present work the reduced-performance curves were determined for 46 tests; all experimental points on these curves are shown in Figure 3.3 to 3.5. Water distribution for all tests is shown in Figure 3.6. Note that a linear

Table 3.6 Major Results of Test

| Test No. | d50c (microns) | Rf (%) | Fz (%) | m (slope) |
|---|---|---|---|---|
| 1 | 126.27 | 10.59 | 7.41 | 1.38 |
| 2 | 115.24 | 8.43 | 7.10 | 1.49 |
| 3 | 169.02 | 9.22 | 7.52 | 1.56 |
| 4 | 103.15 | 54.60 | 15.64 | 1.22 |
| 5 | 144.88 | 47.90 | 17.90 | 1.38 |
| 6 | 176.67 | 38.85 | 15.17 | 1.52 |
| 7 | 292.14 | 7.91 | 4.66 | 2.21 |
| 8 | 255.69 | 9.33 | 7.23 | 1.65 |
| 9 | 321.30 | 23.05 | 9.58 | 2.19 |
| 10 | 344.57 | 35.92 | 14.61 | 1.78 |
| 11 | 322.14 | 26.78 | 13.15 | 1.79 |
| 12 | 456.38 | 21.02 | 16.14 | 2.05 |
| 13 | 412.84 | 23.71 | 17.92 | 1.77 |
| 14 | 1003.92 | 2.42 | 5.40 | 1.48 |
| 15 | 1009.03 | 2.05 | 7.44 | 2.30 |
| 16 | 376.39 | 18.78 | 6.76 | 2.36 |
| 17 | 416.65 | 20.08 | 6.31 | 1.89 |
| 18 | 631.75 | 10.32 | 6.63 | 1.45 |
| 19 | 397.11 | 8.16 | 5.39 | 2.02 |
| 20 | 600.49 | 4.72 | 5.00 | 2.42 |
| 21 | 804.28 | 2.85 | 5.62 | 2.43 |
| 22 | 844.40 | 2.93 | 6.65 | 2.24 |
| 23 | 406.93 | 27.41 | 20.66 | 1.74 |
| 24 | 380.08 | 21.95 | 10.68 | 1.95 |
| 25 | 731.33 | 2.30 | 4.07 | 2.73 |
| 26 | 793.68 | 1.91 | 4.02 | 2.74 |
| 27 | 1917.53 | 2.06 | 9.53 | 2.20 |
| 28 | 1794.43 | 7.20 | 18.87 | 1.42 |
| 29 | 2410.24 | 2.92 | 15.36 | 2.53 |
| 30 | 1448.57 | 9.65 | 18.63 | 1.96 |
| 31 | 205.44 | 10.42 | 8.42 | 1.67 |
| 32 | 226.23 | 5.07 | 8.15 | 1.93 |
| 33 | 267.82 | 3.06 | 7.68 | 2.07 |
| 34 | 218.30 | 21.22 | 29.01 | 1.89 |
| 35 | 319.10 | 80.49 | 40.00 | 1.71 |
| 36 | 2522.74 | 1.51 | 20.11 | 1.58 |
| 37 | 2638.57 | 6.42 | 32.12 | 2.37 |
| 38 | 1935.55 | 8.64 | 32.13 | 1.29 |
| 39 | 275.01 | 7.26 | 11.77 | 2.26 |
| 40 | 894.16 | 2.48 | 14.83 | 2.52 |
| 41 | 240.05 | 40.57 | 28.39 | 1.89 |
| 42 | 597.69 | 2.04 | 10.59 | 2.41 |
| 43 | 1218.29 | 4.10 | 10.48 | 1.75 |
| 44 | 953.45 | 63.61 | 46.88 | 1.73 |
| 45 | 1356.24 | 11.99 | 30.36 | 2.71 |
| 46 | 1562.63 | 7.64 | 28.91 | 1.83 |

relationship exists between water in the fine product and water in the feed.

### 3.6.2 Results of Each Test

The results of each test are given in the Appendix I.

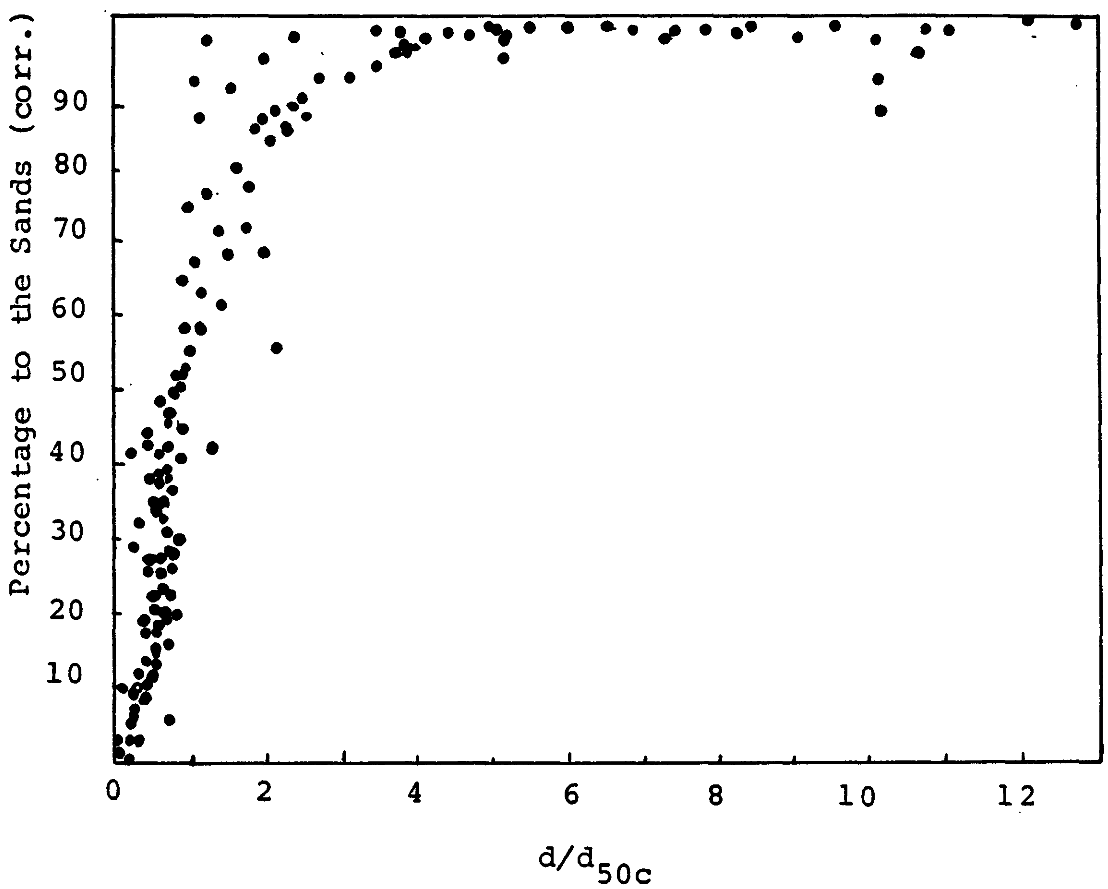



Figure 3.3 Reduced-performance Curve For All Experimental Data

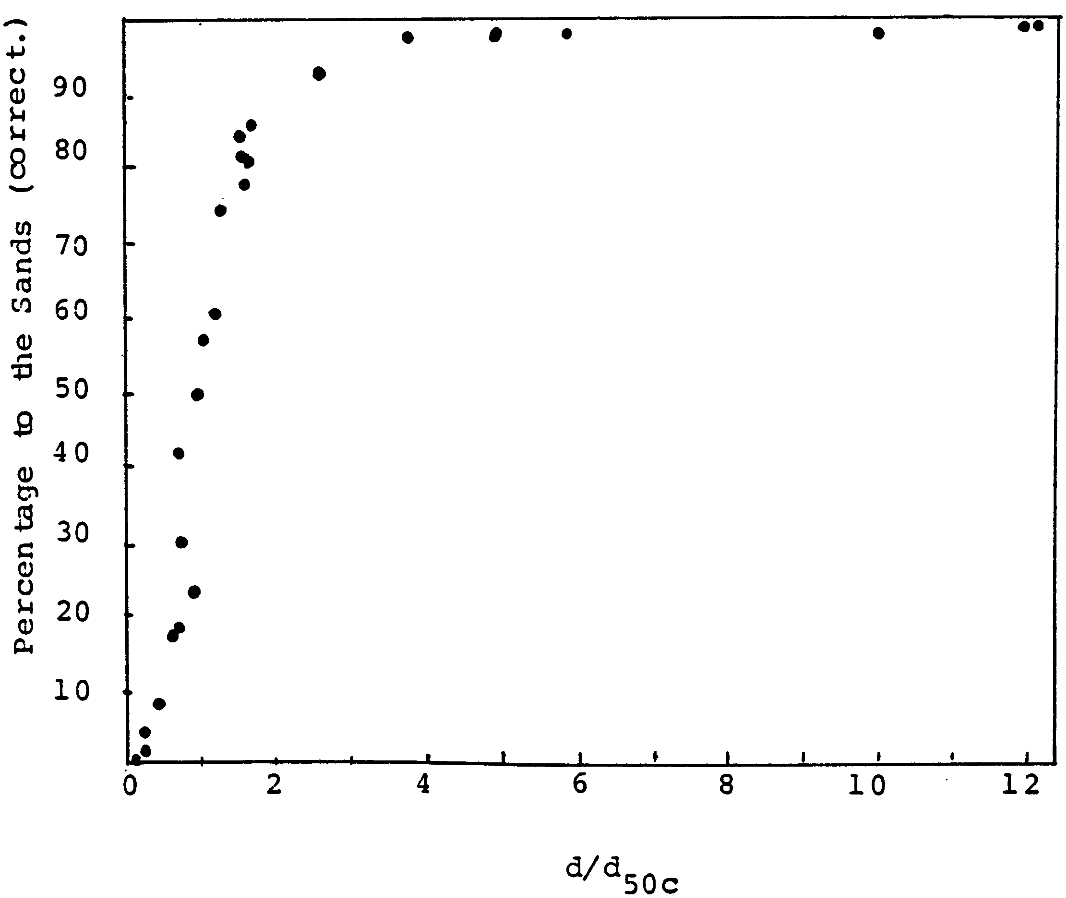



Figure 3.4 Reduced-Performance Curve for Pulp density = 30-40% Experimental Data

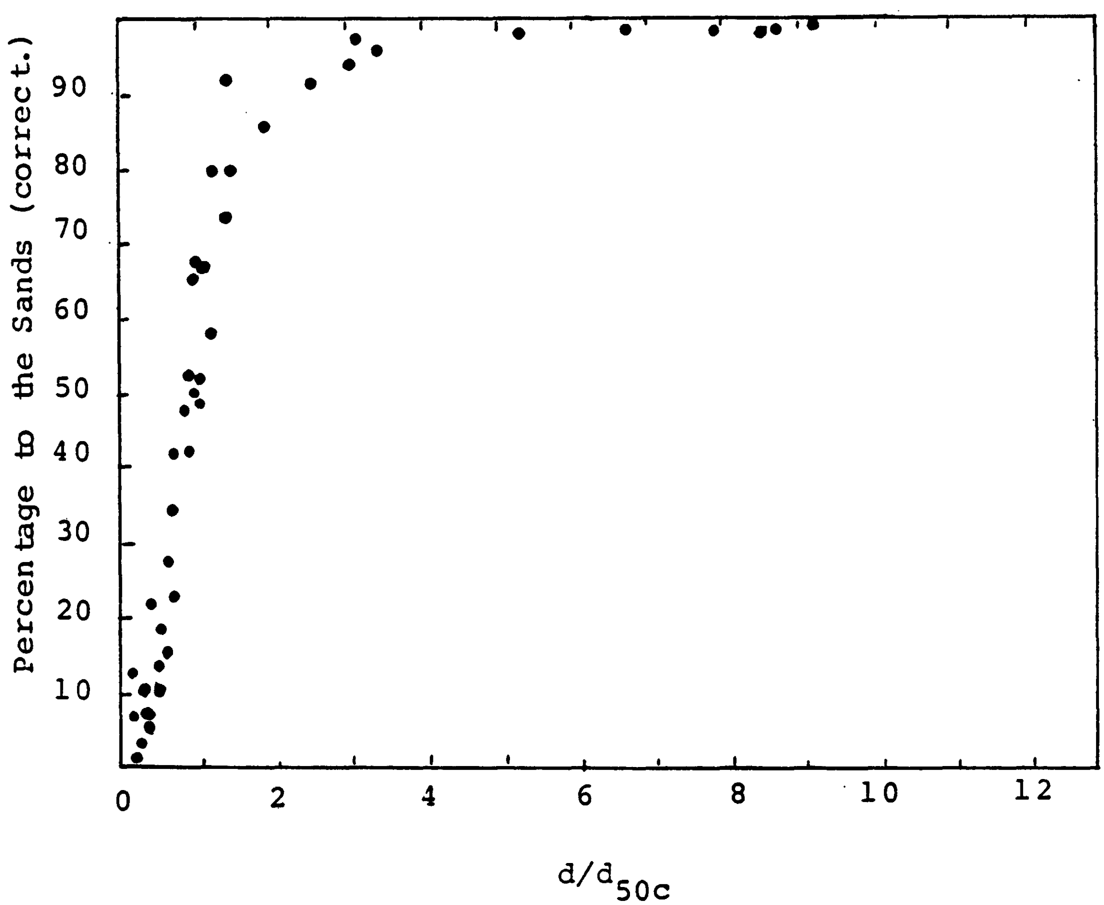



Figure 3.5 Reduced-Performance Curve for +425 microns > 30% Experimental Data

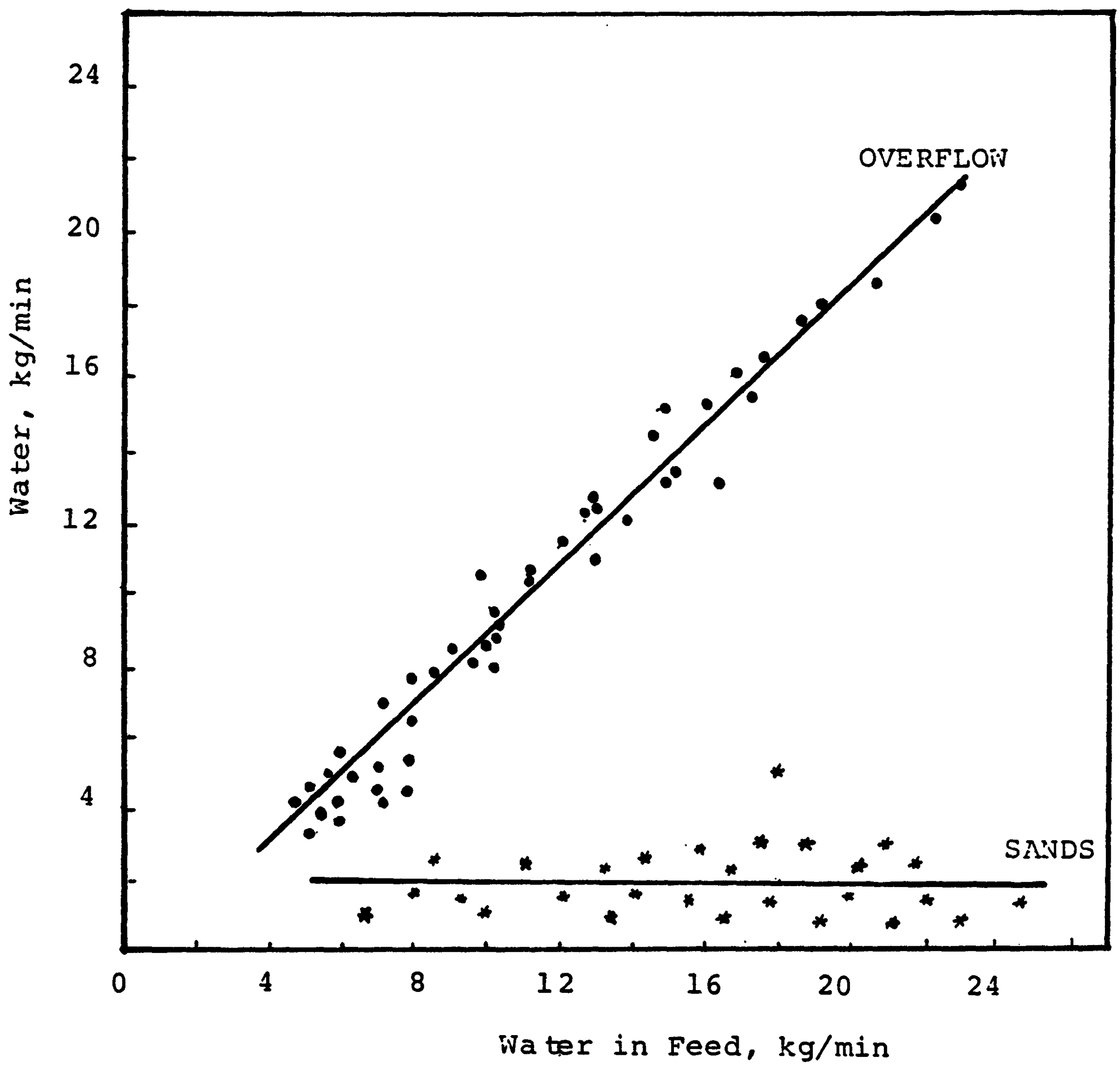



**Figure 3.6 Water Distribution For All Experimental data**

# CHAPTER IV

# DEVELOPING A MATHEMATICAL MODEL OF SPIRAL CLASSIFIER

A mathematical model of a spiral classifier which is suitable for circuit design and optimization by simulation consists of a series of equations which relate the design and operating variables to the separation achieved. As mentioned in Chapter III, a total of 46 experiments were carried out in an effort to develop an applicable mathematical model of the spiral classifier. The design and operating variables studied were: weir height and slope of classifier, the volumetric flow rate, pulp density, % +425 microns and % -53 microns in the feed. A spiral classifier model which relates the above variables to separation has been formulated.

## 4.1 Form of the Model

The particle separation process in spiral classifiers, just as in hydrocyclones, is a probability process in which particles of different size, density, and shape have different probabilities of appearing in the coarse product. In the former, separation was based on gravity force, and in the latter, on centrifugal force; hence the fluid flow patterns within the two machines are not the same (35,36). In spite of the difference, the method for developing a hydrocyclone model is a very useful guide for developing a spiral classifier model.

A spiral classifier model can also be based on concepts of d50c and the reduced-performance curve. The model of a spiral classifier that has been formulated in this study consists of four basic equations which express the cut size, d50c, water split between overflow and sands, percentage of finest size fraction (here it is % -53 microns) in the sands, and sharpness of separation, in terms of the operating and design variabes.

## 4.2 Method of Developing a Mathematical Model

The spiral classifier model presented here is an empirical model which relates all major design and operating variables to the separation achieved. An orthogonal least squares procedure which makes regression techniques greatly simplified (29,37) could not be used because it was difficult to maintain some variables at the set levels. So in this study, the experimental data were processed using a stepwise multiple linear regression program developed by the computer center of the Western Michigan University (38). The program was used to formulate the functional relationships between the measured and calculated parameters (cut size, water split, the finest size fraction in the sands, and sharpness of separation) and the design and operational spiral classifier variables. The linear regression procedure was repeated using different functional variables (such as linear, power, exponential) and different variable combinations, as follows (X1,X2,...,X6 as defined earlier):

Independent Variables:

X1, X2, X3, X4, X5, X6

$X1^2$, $X2^2$, $X3^2$, $X4^2$, $X5^2$, $X6^2$

$X1^3$, $X2^3$, $X3^3$, $X4^3$, $X5^3$, $X6^3$

X1X2, X1X3, X1X4, X1X5, X1X6

X2X3, X2X4, X2X5, X2X6

X3X4, X3X5, X3X6

X4X5, X4X6

X5X6

X1X2X3, X2X3X4, X3X4X5, X4X5X6, X1X2X6, X1X3X4,.....

ln(X1), ln(X2),........, ln(X6)

ln(X1X2), ln(X1X3),.....

Dependent Variables:

d50c, ln(d50c)

Rf, ln(Rf)

Fz, ln(Fz)

m, ln(m)

The mean sum of the residuals squared was used as the criterion as to the goodness of fit. Only variables which were significant at the 99.5 % confidence level were included the regression equations.

## 4.3 The d50c Equation

It has become common practice to express the cut size in terms of the d50c size. For pure dolomite classified in a small 220 by 1300 mm spiral classifier , the regression relationship between ln(d50c) and classifier variables is:

$$\ln(d50c) = -0.3636 + 0.1638X2 + 0.0036X3^2 + 0.00096X4^2 + 0.00099X1X2 - 0.004134X2X3 \quad (4.1)$$

As shown in Table 4.3, Eq.4.1 fits the data from 46 tests with a correlation coefficient of 0.963. A comparision of the observed values, and the values calculated from the regression equation is shown in Fig. 4.3.

Equation 4.1 indicates that the ln(d50c) is: 1) directly proportional to the pulp density, the second power of the percentage of +425 microns and -53 microns in the feed, and the product of the volumetric flow rate and the pulp density; and 2) decreases proportionaly to the product of pulp density and percentage of % +425 microns in the feed. The effect of each of the variables is discussed in more detail below.

The Feed Pulp Density

The pulp density of the feed was found to be a variable which greatly influenced the magnitude of d50c. It is felt that the principal reason for this is an increase in the effective pulp viscosity which occurs with increasing solids content. Hindered settling and underflow crowding may also be factors.

Fig. 4.1 shows that the d50c increases with increasing feed pulp density, with a greater increase when the pulp density exceeds 50 %.

Lynch (2,14) and Jull (55) found similar results for the hydrocyclone classifier. The different kinds of classifier show the same trend, with large increases in the d50c size as the feed pulp density increases.

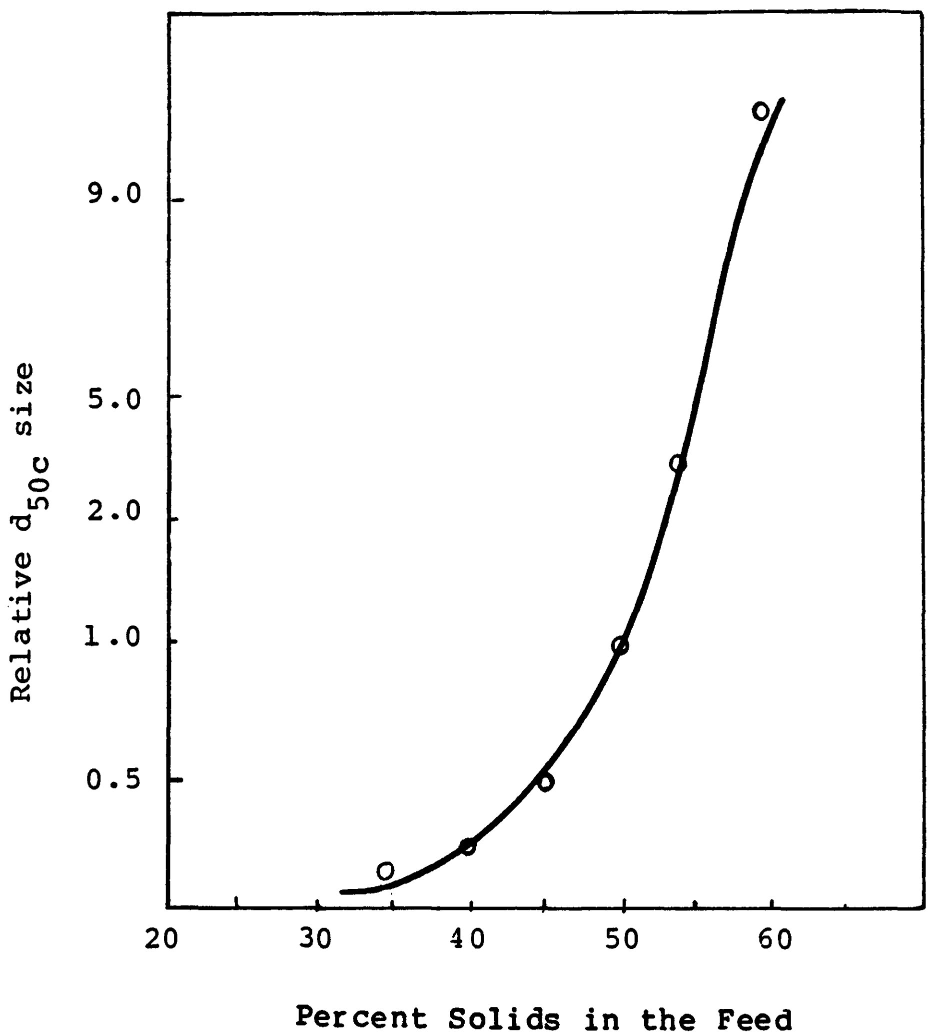



Figure 4.1 The Relationship Between d50c and Pulp Density

The Particle Size Distribution

It has been established (23,56) that the size distribution of the feed solids also affects the apparent viscosity of slurries. The equation shows that the ln(d50c) is directly proportional to the square of X4 (i.e., the % -53 microns in the feed). Note that in Eq. 4.1 the coarse size also significantly influences d50c; the reason for this may simply be that the more coarse particles report to both overflow and sand as the fraction of the coarse size increases.

## 4.4 The Reduced-performance Curve Equation

The reduced-performance curve is a measure of the probability of the appearance of particles in the sand due to gravity action alone. Equations which have been used to define reduced-performance are:

$$Ec = \{e^{\alpha x} - 1\}/\{e^{\alpha x} + e^{\alpha} - 2\} \qquad (2.3)$$

and

$$Ec = 1 - \exp(-0.693X^{m}) \qquad (2.4)$$

Some workers (39) use equation 2.4 rather than 2.3, and consider that the latter represents full-scale classifier performance data with good agreement using values of m in the range of 1.5 to 3.5 (40).

Equation 2.4 can be linearized by plotting lnln(1/(1-Ec)) versus ln(d). The resulting best-fit line will have a slope equal to m and the d50c size will correspond to the point where 1/(1-Ec) is equal to 2. This can also be done with the computer. From equation 2.4:

$$1 - Ec = \exp(-0.693(d/d50c)^{m})$$

$$1/\{1-Ec\} = \exp(0.693(d/d50c)^{m})$$

$$\ln\{1/(1-Ec)\} = 0.693(d/d50c)^{m}$$

$$\ln \ln\{1/(1-Ec)\} = \{\ln(0.693)-m\ln(d50c)\}+m \ln(d) \qquad \ldots (4.2)$$

Where {ln(0.693)-m ln(d50c)} is a constant term of the regression equation.

Because m and the constant term can be obtained using a regression technique, d50c can then be calculated from equation 4.3 as follows:

$$\ln(0.693)-m\ln(d50c)=constant=C$$

$$m \ln(d50c)=\ln(0.693)-C$$

$$\ln(d50c)=\ln(0.693)-C/m$$

hence $$d50c=\exp((\ln 0.693-C)/m) \qquad \ldots (4.3)$$

In this study, equation 2.4 was used. The regression equation produced from the experimental data (see Table 3.4) is :

$$m=-1.5156+0.08944X4-0.000014X4^3+0.001812X3^2$$
$$-0.001144X1X2+0.65789\ln(X1X6)-1.19477\ln(X3)$$
$$+0.05844X1 \quad \ldots (4.4)$$

In his hydrocyclone model, Plitt (7) obtained a regression equation for m with a correlation coefficient of 0.75. Equation 4.4 has the poorest correlation coefficient (0.79) among all the equations which make up the mathematical model of spiral classifier. This result indicates that more work is required in this area to firmly establish the relationship between sharpness of separation and the operating and design variables in both of the hydrocyclone and spiral classifier models.

The calculation of efficiency for a test is given in Table 4.1.

Fig. 4.2 shows that for test number 3, the d50c is determined to be 169 microns, and the slope of the reduced-performace curve, m, is 1.56. From the data given in Table 4.1, it can be seen that the model fits the experimental data well in the size range from 174 to 992 microns, and the difference between the test data and calculated data becomes larger in the size less than 104 microns. In order to increase accuracy, it may be necessary to develop the model separatly for coarse size and fine size fractions.

Table 4.1 Calculation of efficiency

| Size (micron) | Ea (%) | Ec (%) | Model Ec (m=1.56)(%) |
|---|---|---|---|
| - | 100.00 | 100.00 | - |
| 992 | 97.84 | 97.61 | 99.96 |
| 350 | 93.58 | 92.89 | 88.36 |
| 248 | 73.22 | 70.34 | 71.65 |
| 174 | 56.01 | 51.28 | 51.83 |
| 104 | 39.78 | 33.30 | 27.76 |
| 63 | 16.30 | 7.29 | 13.70 |

## 4.5 The Water Split Equation

From Fig.3.6 it can be seen that a linear relationship exists between the water in the overflow and the water in the feed over a very wide range of operating conditions. For a given classifier, the operating variables which have the greatest influence on this relationship are the volumetric flow rate, pulp density and the weir height of the classifier.

The final form of the regression equation is:

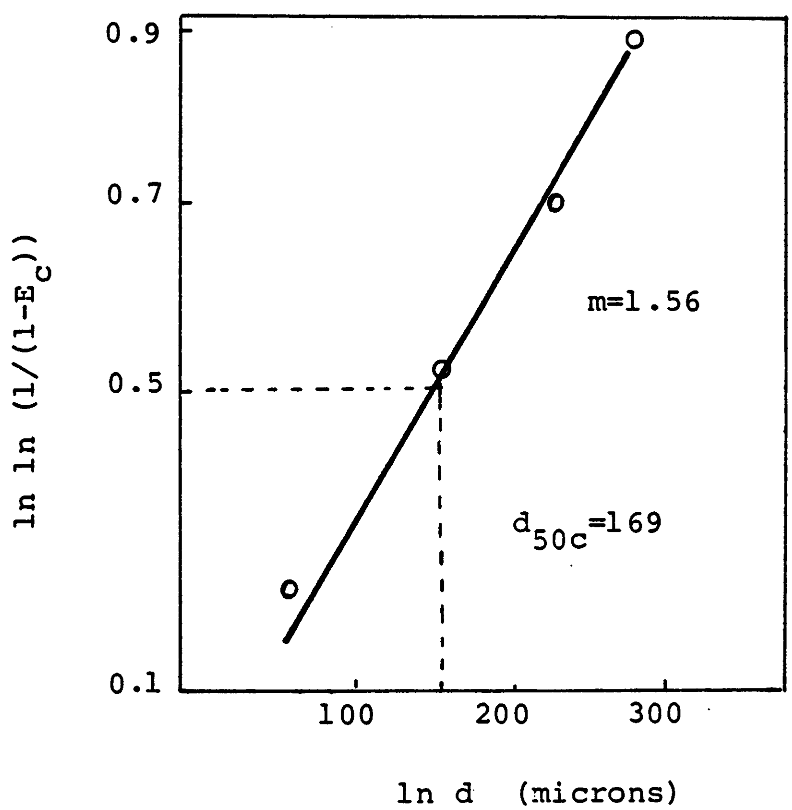



Figure 4.2 Sample Plot of Classification Test of Spiral Classifier (refer to Test NO.3)

$$\ln(Rf)=4.7074+0.003361X1^2-0.003505X3^2-0.001168X1X5$$
$$+0.01486X3X6-0.003885X5X6+0.0000012X5 \quad \ldots (4.5)$$

Equation 4.5 fits the experimental data with a correlation coefficient of 0.954.

4.6 The "Finest Size Fraction" Split Equation

As described in Chapter II and III, the actual performance curve of a hydrocyclone and a spiral classifier will not pass through the origin. The reason for this has been explained by Kelsall (11). He suggested that, independent of he centrifugal force acting on the particles, if Rf is the fraction of feed fluid reporting to the underflow, Rf of all sizes of particles are discharged through the spigot. Therefore, separation due to centrifugal action, or corrected efficiency, Ec is given by

$$Ec = \{Ea-Rf\}/\{1-Rf\} \qquad (2.2)$$

Since then, Eq.2.2 has been widely used to calculate the corrected-efficiency of a hydrocyclone (2,7,9,14,39), and Plitt considered that this equation can also be used for a gravity type classifier (10).

The use of Equation 2.2 for the spiral classifier was considered. However, this equation is not completely satisfactory, as demonstrated by the selected results shown in Table 4.2.

It is obvious that the Ec value of the final size fraction will be negative if Equation 2.2 is used to calculate Ec, because Rf is greater than Ea (-53 microns) in all these cases. There is no way to explain this phenomenon. Austin (41) has also found that the water split and by-pass fraction are not the same. For this reason Equation 3.3 is adopted here instead of Equation 2.2 to calculate Ec. The form of this equation is:

$$Ec = \{Ea-Fz\}/\{1-Fz\} \quad (3.3)$$

Where:

Fz = % -53 microns in the sands

The regression relationship between Fz and the operating variables is:

$$Fz = -19.3423+1.7429X1+1.2272X4+0.03768X1X3 -0.01832X1X5+0.01549X2X4-0.010625X3X5 +0.068742X3X6-0.12691X4X6+0.0000094X5^3 \quad \ldots (4.6)$$

Equation 4.6 shows that the major operating variables which affect the Fz value are the volumetric flow rate, %

Table 4.2 Typical Test Results

| Run | Size (microns) | Size Distribution (%) O/F | Sand | Feed | Ea (%) |
|---|---|---|---|---|---|
| | 2803 | 0.00 | 0.03 | 0.02 | 100.00 |
| | 992 | 2.64 | 32.02 | 23.37 | 96.67 |
| | 350 | 2.64 | 16.64 | 12.52 | 93.79 |
| 4 | 248 | 6.61 | 12.86 | 11.02 | 82.33 |
| | 174 | 4.41 | 7.52 | 6.60 | 80.33 |
| | 104 | 4.64 | 4.45 | 4.51 | 69.67 |
| | 63 | 20.47 | 10.84 | 13.68 | 55.92 |
| | -63 | 58.59 | 15.64 | 28.69 | 39.00 |

Rf = 54.60%
Mass flowrate of overflow = 1.626 kg/min
Mass flowrate of sands = 3.895 kg/min

| | | | | | |
|---|---|---|---|---|---|
| | 2803 | 0.00 | 0.97 | 0.55 | 100.00 |
| | 992 | 2.43 | 65.15 | 37.71 | 97.18 |
| | 350 | 4.96 | 9.68 | 7.61 | 71.50 |
| 9 | 248 | 7.61 | 5.32 | 6.32 | 47.33 |
| | 174 | 8.49 | 4.23 | 6.09 | 39.04 |
| | 104 | 4.09 | 0.97 | 2.34 | 23.36 |
| | 63 | 21.14 | 4.10 | 11.56 | 19.95 |
| | -63 | 51.28 | 9.58 | 27.83 | 19.36 |

Rf = 23.05%
Mass flowrate of overflow = 4.45 kg/min
Mass flowrate of sands = 5.72 kg/min

| | | | | | |
|---|---|---|---|---|---|
| | 2803 | 0.00 | 1.31 | 0.12 | 100.00 |
| | 992 | 6.95 | 66.83 | 12.63 | 50.20 |
| | 350 | 6.26 | 9.88 | 6.60 | 14.19 |
| 14 | 248 | 10.60 | 5.60 | 10.13 | 5.25 |
| | 174 | 9.05 | 3.93 | 8.56 | 4.43 |
| | 104 | 16.68 | 4.93 | 15.57 | 3.00 |
| | 63 | 8.12 | 2.12 | 7.55 | 2.66 |
| | -63 | 42.34 | 5.40 | 38.84 | 1.32 |

Rf = 2.42%
Mass flowrate of overflow = 10.93 kg/min
Mass flowrate of sands = 1.146 kg/min

-53 microns in the feed, pulp density, weir height and the slope of the classifier. These results are logical in respect to both of theory and practice.

## 4.7 Summary

A mathematical model of a small spiral classifier has been formulated based on the experimental data. This model consists of four basic equations which are the d50c equation, reduced-performance curve equation, water split equation and the finest size fraction split equation. In general, all the above equations fit the test data with high correlation coefficients excepting equation 4.4.

The results of the multiple linear regression for each are given in Table 4.3, 4.4, 4.5, and 4.6, respectively. The nomenclature used in the above Tables is as follows:

D.F = degree of freedom

S.SQ = sum of squares

M.S = mean square

M.C.C = multiple correlation coefficient

F = F value (34)

Comparison of the observed values, and the values calculated from the model, are given in the Figure 4.3 through 4.6, respectively.

Table 4.3. The Results of Multiple Linear Regression (for d50c Equation)

| Source of Variation | DF | S.SQ | MS | MCC | F Eq. | F F-d |
|---|---|---|---|---|---|---|
| 01234567890123456789 | | | | | | |
| Regression | 5 | 33.07 | 6.61539 | 0.96 | 102 | 3.51 |
| Residual | 40 | 2.5953 | 0.06488 | | | |
| Total | 45 | 35.6722 | | | | |

Note: Eq. : From Equation
F-d : From F distribution

Table 4.4. The Results of Multiple Linear Regression (for m Equation)

| Source of Variation | DF | S.SQ | MS | MCC | F Eq. | F F-d |
|---|---|---|---|---|---|---|
| Regression | 7 | 5.726 | 0.818 | 0.79 | 9.02 | 3.3-3.12 |
| Residuals | 38 | 3.444 | 0.096 | | | |
| Total | 45 | 9.170 | | | | |

Note: Eq. : From Equation
F-d : From F distribution

Table 4.5. The Results of Multiple Linear Regression (for Rf Equation)

| Source of Variation | DF | S.SQ | MS | MCC | F Eq. | F F-d |
|---|---|---|---|---|---|---|
| Regression | 6 | 48.055 | 8.009 | 0.954 6 | 5.43 | 3.47-3.29 |
| Residuals | 39 | 4.774 | 0.122 | | | |
| Total | 45 | 52.829 | | | | |

Note: Eq. : From Equation
F-d : From F distribution

Table 4.6. The Results of Multiple Linear Regression (for Fz equation)

| Source of Variation | DF | S.SQ | MS | MCC | F Eq. | F F-d |
|---|---|---|---|---|---|---|
| Regression | 9 | 4231.68 | 470.186 | 0.95 | 36.00 | 3.07-2.89 |
| Residuals | 36 | 470.139 | 13.059 | | | |
| Total | 45 | 4701.82 | | | | |

Note Eq. : From Equation
F-d : From F distribution

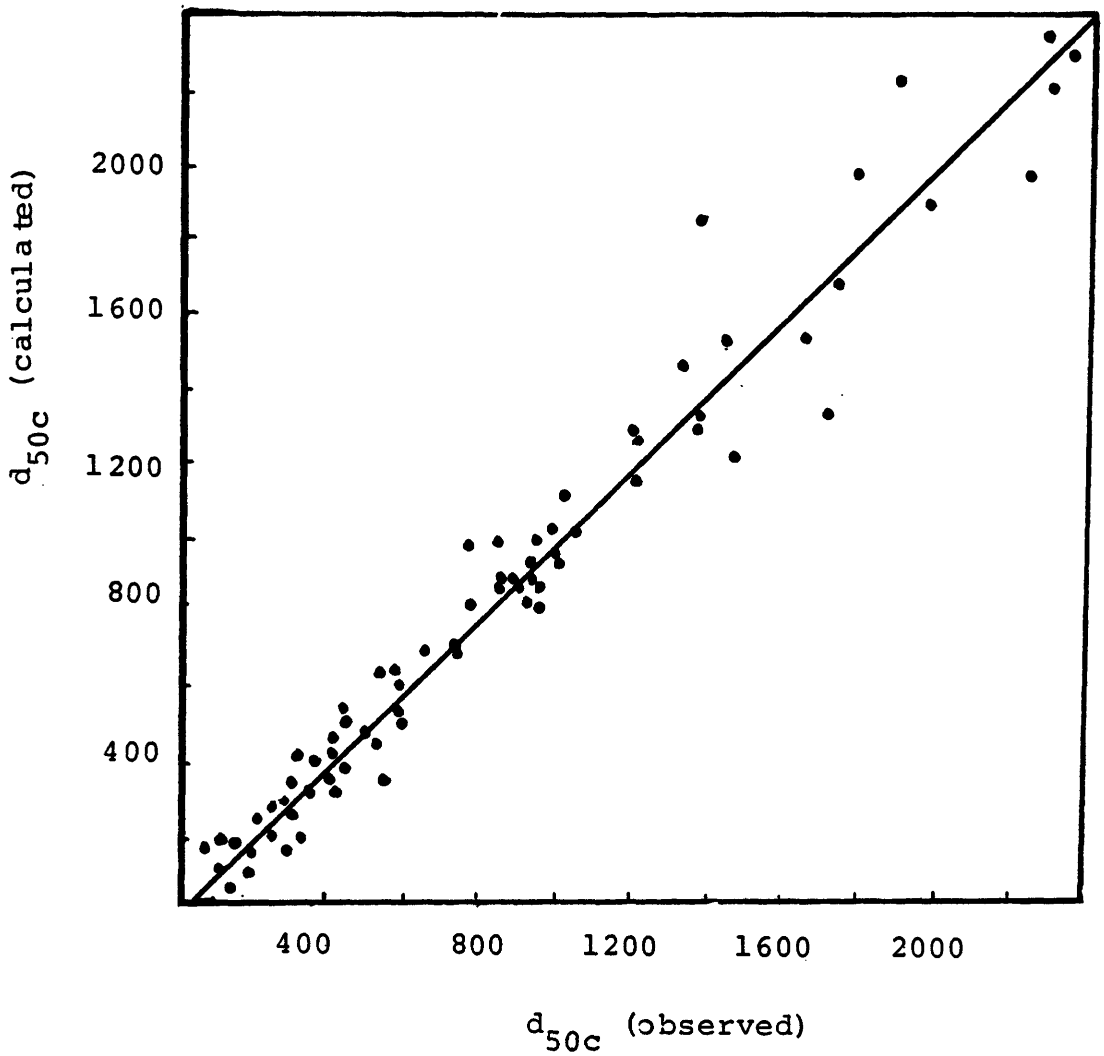



Figure 4.3 Comparison of Observed and Calculated Values for d50 (Corrected)

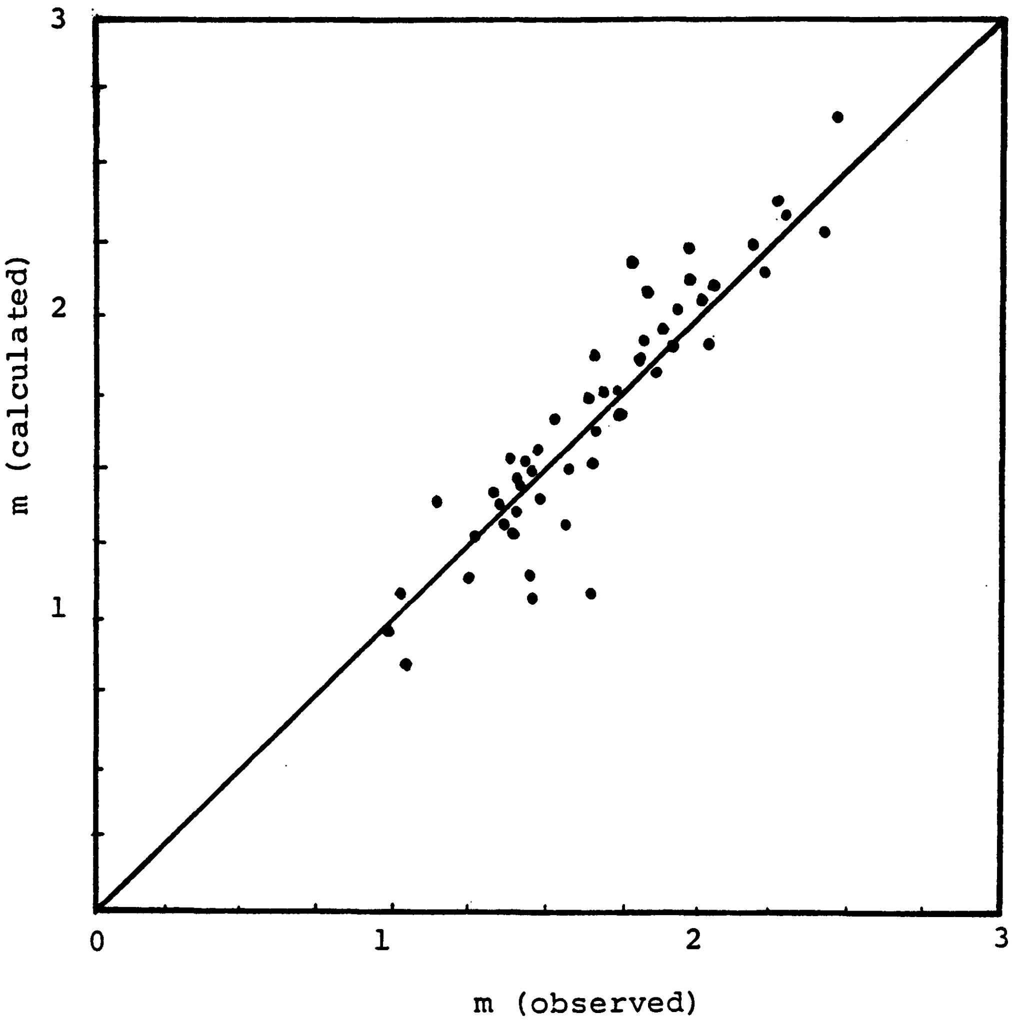



Figure 4.4 Comparison of Observed and Calculated Values for m

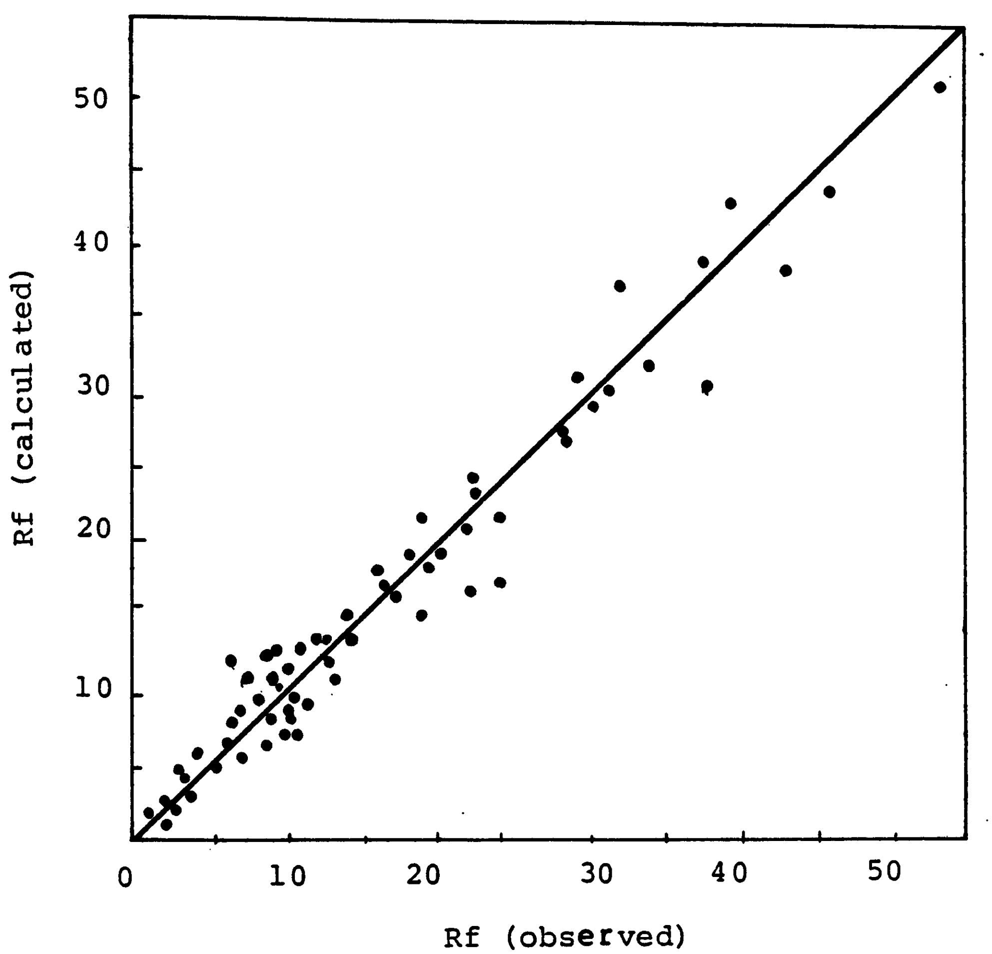



**Figure 4.5 Comparison ot Observed and Calculated Values for Rf (Water Split)**

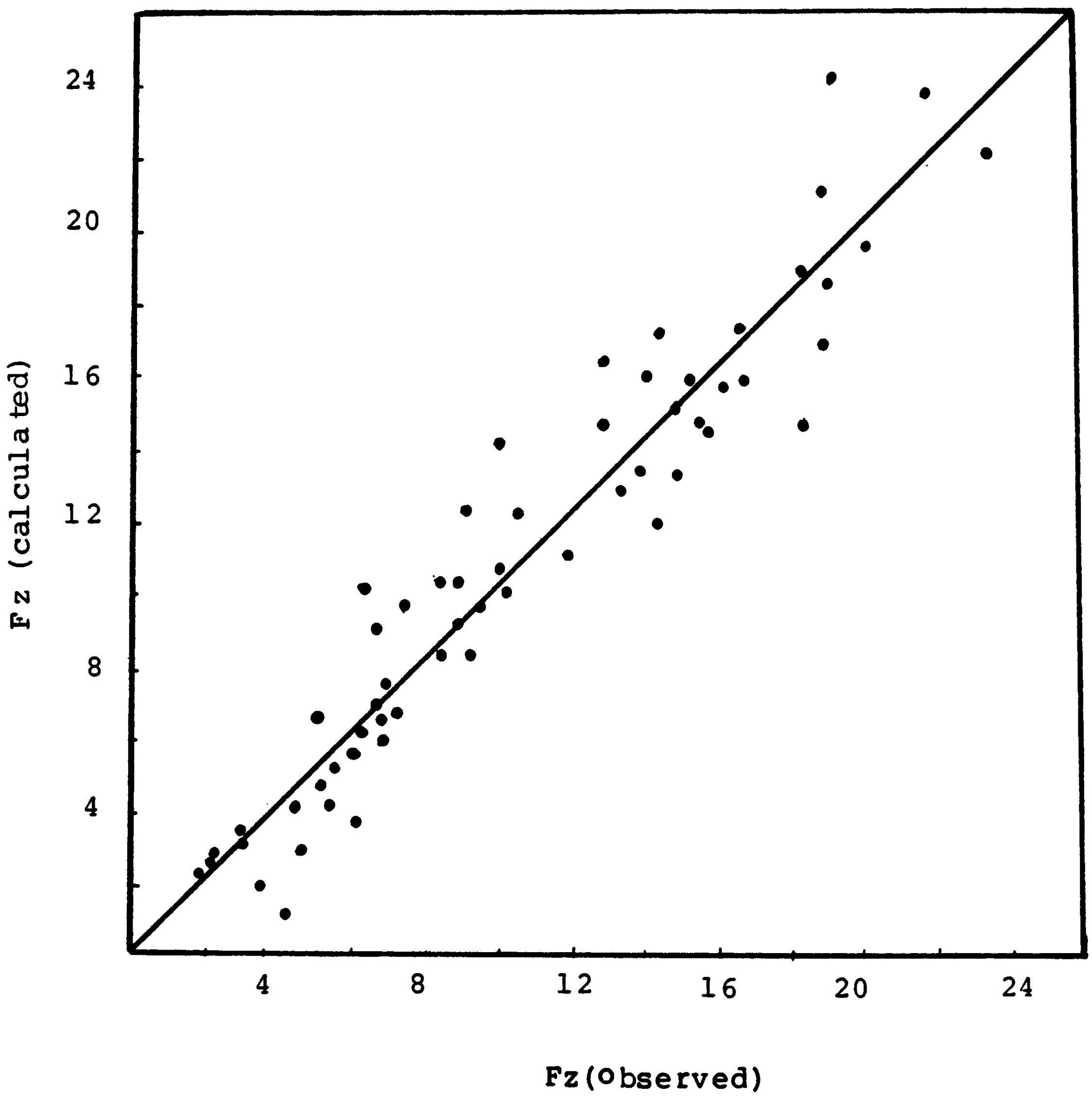



Figure 4.6 Comparison of Observed and Calculated Values for Fz

# CHAPTER V

# GRINDING CIRCUIT SIMULATION

The possibility of representing a grinding-classifying circuit by means of a series of mathematical equations, developed empirically from a broad base of data or theoretically from the physical characteristics of the grinding and classifying process, has generated tremendous research activity in this field (40-49). It is obvious that modeling and simulation in mineral processing will become more and more important because of the need for optimization and automatic control (51,65,68).

The simulation study presented here is an attempt to model a closed grinding-classifying circuit using a plug flow cumulative-basis first order kinetic model (61) for a ball mill, and the spiral classifier model which has been formulated by the author in this thesis. The results obtained were satisfactory within acceptable limits.

## 5.1 Simulation Fundamentals

### 5.1.1 Ball Mill Model

The ball mill model which has been used in this closed grinding-classifying circuit is based on the breakage rate described by a first order rate equation. The breakage rate is the fractional rate at which a given size of particle disappears, having been broken into smaller particles, and the resultant cumulative distribution of the daughter fragments is described as the breakage function (9,45,52). The breakage rate depends markedly on the hardness of the material and the equipment in which the material would be broken (53,54). Various investigators (22,66,67) have shown that the rate of breakage in a ball mill can be described by Equation 5.1.

The form of the first order rate equation is:

$$dm_i / dt = -K_i m_i \qquad (5.1)$$

Where:

$m_i$ = mass fraction in size i

$K_i$ = rate of breakage out of size fraction i, the first-order rate constant

t = time

In batch grinding, all the material remains in the mill for the required time. Plug flow through a continuous mill is in fact equivalent to batch grinding, with the average residence time equal to the batch grinding time. Under this condition part of the material in any size fraction is disappearing because of breakage, while other material is entering the size fraction as a result of breakage of particles in larger size fractions.

The breakage rate for different size fractions can be calculated using the integrated form of Equation 5.1 which is

$$\ln m_i = \ln m_{oi} - K_i t \qquad (5.2)$$

Where, $m_{oi}$ is the mass fraction in the ith size in the ball mill at time zero and the other terms are as previously defined. Equation 5.2 can be written in the following form:

$$m(t) = m(0)\exp(-K_i t) \qquad (5.3)$$

Equation 5.3 is the final form of the kinetic plug flow model which was used in the simulation of this study.

5.1.2 Spiral Classifier Model

As discussed in Chapter IV, the spiral classifier model consists of four equations. They are expressed in equation 4.1, 4.4, 4.5 and 4.6, respectively.

5.1.3 Mass Balance Equation

The closed grinding-classifier circuit to be simulated consists of a ball mill and a spiral classifier (see Figure 5.1).

The final mass balance equations which will be needed for simulating the circuit are:

1) Around the classifier

Water balance:

$$WW2 = WW1+WW5 \quad (5.5)$$

$$WW2+W2 = WW3+WW4 \quad (5.6)$$

Solids balance:

$$SW2 = SW1+SW5 \quad (5.7)$$

$$SW2 = SW3+SW4 \quad (5.8)$$

Solids balance for each size fraction:

$$SW2M2(di) = SW1M1(di)+SW5M5(di) \quad (5.9)$$

$$SW2M2(di) = SW3M3(di)+SW4M4(di) \quad (5.10)$$

2) Around the ball mill

Water balance:

$$WW3+W3 = WW5 \quad (5.11)$$

Solids balance:

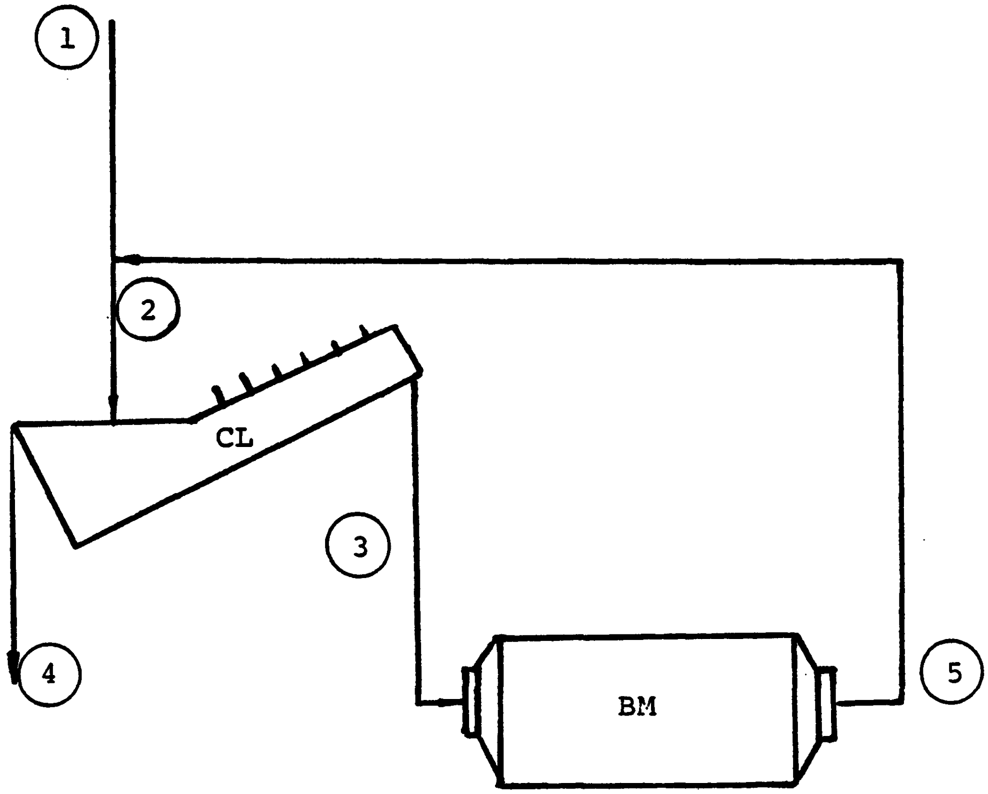
$$SW3 = SW5 \quad (5.12)$$

Where:

WWi = Water mass in the ith stream

SWi = solids mass in the ith stream

Mi(di) = mass percent of size di in the ith stream




BM ball mill
CL classifier

Figure 5.1 Closed grinding-classifying circuit

W2 = water addition to the classifier

W3 = water addition to the ball mill

i=1, 2, ...., 5

## 5.2 Simulation Program

The flow chart of Figure 5.2 shows schematically the computer program developed to simulate the closed grind-classifying circuit shown in Figure 5.1; the program is shown in Appendix II. The program consists of five parts, which are: main program, input subroutine, spiral classifier subroutine, ball mill subroutine and output subroutine.

An iteration method was used in this program. Convergence was considered achieved when the difference between the solids mass in the product (overflow) and in the new feed is less than 0.1 %. However, if the number of iterations was over 30 and convergence was still not achieved, then the program also went to the output subroutine and the final iteration results were given as output.

## 5.3 Simulation Results

The following is the printout of a simulated grinding-classification operation:

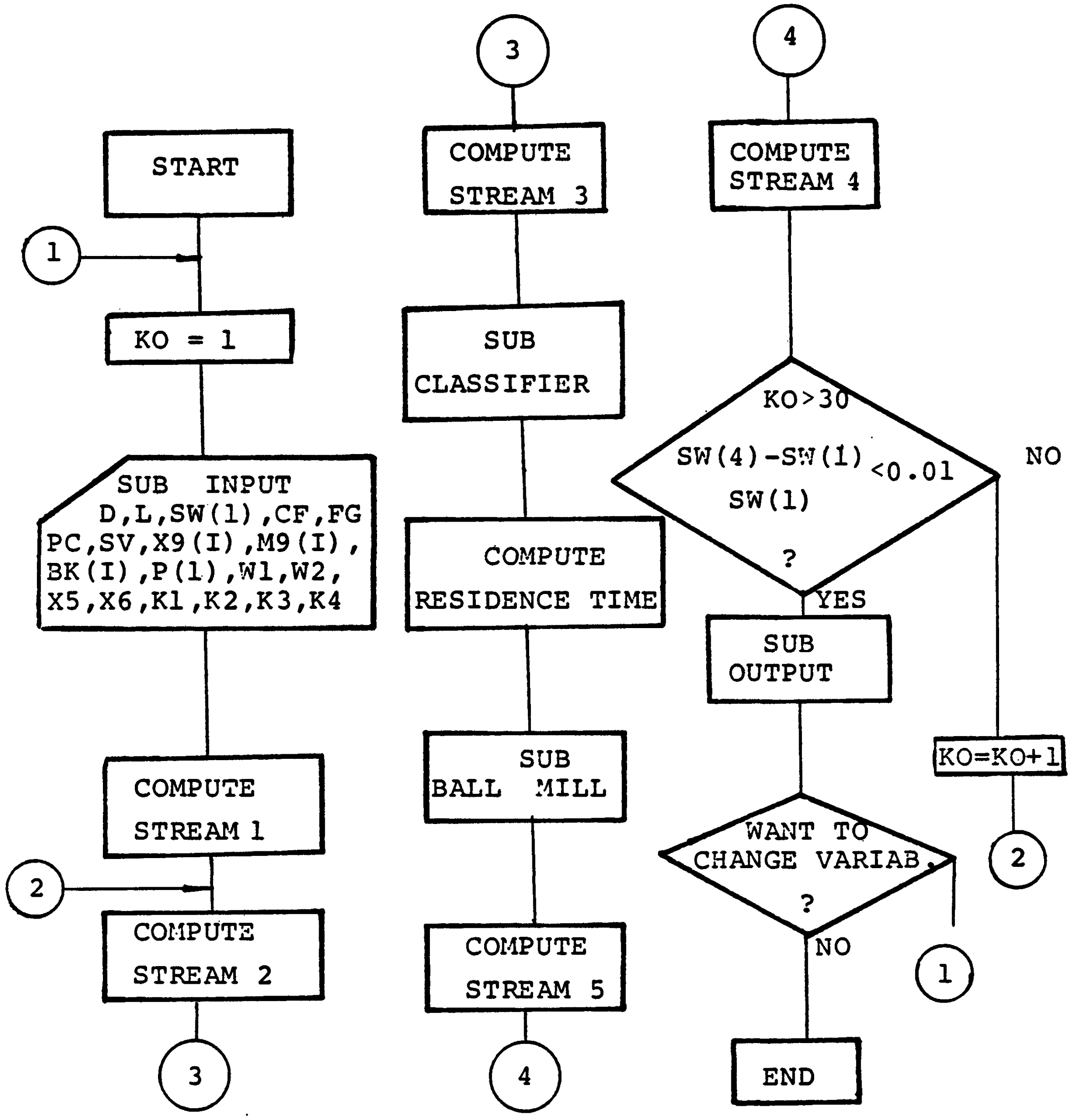



Figure 5.2 Simplified flow-chart of the computer program to simulate the closed grinding-classifying circuit

Table 5.1 Simulation Results

MEAN RESIDENCE TIME = 1.14 MIN

CIRCULATING LOAD = 123.33 PCT

WEIGHT PERCENT RETAINED OF STREAMS INDICATED

STREAM NO. 1

| SIZE | PCT RETAINED |
|---|---|
| 598 | 20.06 |
| 425 | 3.56 |
| 300 | 3.98 |
| 212 | 5.33 |
| 148 | 5.49 |
| 106 | 7.00 |
| 75 | 7.96 |
| 53 | 6.91 |
| -53 | 39.71 |

STREAM NO. 2

| SIZE | PCT RETAINED |
|---|---|
| 598 | 20.54 |
| 425 | 4.01 |
| 300 | 5.29 |
| 212 | 11.94 |
| 148 | 13.78 |
| 106 | 10.72 |
| 75 | 7.50 |
| 53 | 5.33 |
| -53 | 20.89 |

Table 5.1 Simulation Results (continued)

STREAM NO. 3

| SIZE | PCT RETAINED |
|---|---|
| 598 | 37.19 |
| 425 | 7.26 |
| 300 | 9.41 |
| 212 | 18.72 |
| 148 | 15.69 |
| 106 | 7.59 |
| 75 | 3.02 |
| 53 | 1.14 |
| -53 | 0.00 |

STREAM NO. 4

| SIZE | PCT RETAINED |
|---|---|
| 598 | 0.00 |
| 425 | 0.00 |
| 300 | 0.21 |
| 212 | 3.58 |
| 148 | 11.43 |
| 106 | 14.59 |
| 75 | 13.03 |
| 53 | 10.49 |
| -53 | 46.66 |

STREAM NO. 5

| SIZE | PCT RETAINED |
|---|---|
| 598 | 21.01 |
| 425 | 4.40 |
| 300 | 6.39 |
| 212 | 17.36 |
| 148 | 20.43 |
| 106 | 13.67 |
| 75 | 7.10 |
| 53 | 4.03 |
| -53 | 5.62 |

Table 5.1 Simulation Results (continued)

WEIGHT PCT SOLIDS

STREAM 1 =85
STREAM 2 =37.0440852
STREAM 2 =43.2615322
STREAM 4 =22.1603026
STREAM 5 =43.2615322

SPIRAL CLASSIFIER SELECTIVITY INDICES,PCT

| SIZE | EC(I) |
|---|---|
| 598 | 100.00 |
| 504 | 99.97 |
| 357 | 98.22 |
| 252 | 86.59 |
| 177 | 62.88 |
| 125 | 39.08 |
| 89 | 22.21 |
| 63 | 11.80 |

Table 5.2 Input Data for the Simulation

CUMULATIVE-BASIS BREAKAGE RATE

| SIZE | BREAK.RATE |
|---|---|
| 598 | 0.500 |
| 425 | 0.490 |
| 300 | 0.461 |
| 212 | 0.341 |
| 148 | 0.208 |
| 106 | 0.123 |
| 75 | 0.079 |
| 53 | 0.051 |
| -53 | 0.000 |

INPUT DATA FOR THIS SIMULATION(CONTIUED)

BALL MILL HOLD-UP = .01627776 METRIC TONNES

FRESH FEED TONNAGE = .3 MTPH

WATER FLOW RATE ADDED IN THE CLASSIFIER,TPH=.4

WATER SPLIT FACTOR, RF = 7.48915583 PCT

ORE SPECIFIC GRAVITY = 3 G/CC

# CHAPTER VI

# DISCUSSION

## 6.1 The Experiments

The main objective was the development of a suitable experimental technique to obtain experimental results in which the experimental error is as small as possible. Generally speaking, the results in this study are satisfactory within acceptable limits, as mentioned in Chapter III and IV, but it would be possible to make the experimental results more accurate with some changes in experimental technique.

### 6.1.1 Design of Experimental Flowsheet

The experimental flowsheet shown in Figure 3.2 was a closed circuit in which the overflow of the spiral classifier was combined with sands product and returned to the sump as the feed of the classifier. The advantages of this flowsheet were: 1) to minimize experimental materials, and 2) to decrease preparatory work for the tests. It is obvious that the major shortcomings of this flowsheet were: 1) The effect on steady-state operation of the classifier as samples were being taken; 2) It was difficult to maintain the size distribution, pulp density and volumetric flow rate at constant values; 3) The accuracy of the experiments was therefore decreased. Thus, a better experimental flowsheet would be an open circut in which the overflow and sands were not be returned to the sump as feed to the classifier.

6.1.2 Experimental Accuracy

In order to maintain a steady operation of the classifier and increase the experimental accuracy under the conditions of closed circuit operation, certain measures had to be adopted:

1) Examining the mass flow rate of slurry to make sure that the absolute value of the difference between the feed and the sum of the overflow and sands was less than 5 % before each sampling;

2) After measuring each operating variable the samples were then taken;

3) After each sampling, the new material and water were added to the classification circuit based on the mass of slurry samples removed and the condition of the next test;

4) Samples of the overflow, sands and feed were taken at the same time to check the experimental error. Tests were repeated if the experimental error was outside the acceptable limits. In addition, some tests were duplicated.

## 6.2 The Mathematical Model

As described above, a mathematical model of a spiral classifier was formulated based on the concepts of d50c and the reduced-performance curve. As there were differences between hyrdocyclone models and the spiral classifier performance, it is necessary to discuss some major complexities which arose during the process of development of the mathematical model.

### 6.2.1 Determination of the Corrected Performance Curve

It is well known that the actual performance curve for a hydrocyclone does not pass through the origin. Early in the 1950's, Kelsall (11) explained the reason for this. It is generally assumed that the solids of all sizes are entrained by the coarse product liquid. In other words, this entrainment effect manifests itself as an intercept on the ordinate of the performance curve which normally corresponds, at least approximately, to the fraction of water recovered to coarse product, i.e., $Ec \rightarrow Rf$, as $d \rightarrow 0$ (see Figure 2.1). Therefore, the corrected efficiency, Ec is shown as Equation 2.2. This equation has commonly been used to calculate Ec for the hydrocyclone (2,7,9,10,14,39,57,59). But it is not in agreement with test results reported in Chapter III, and Austin (41) has pointed out the same problem for a hydrocyclone. This question is now discussed in more detail.

Lynch (2,14) postulated that the two major mechanisms by which particles enter the coarse product are entrainment and classification which can be expressed mathematically as follows:

$$Ea = a + Ec(i) \qquad (6.1)$$

Where Ea(i) is the mass fraction of size interval i in feed reporting to the underflow because of entrainment and classification

Ec(i) = the mass fraction of size interval i in feed reporting to the underflow because of classification only

a = by-pass fraction (no classification).

Although the above postulation must be correct, there still exist two major questions: 1) Is it correct to consider a = Rf? 2) Is the entrainment effect on the coarse and fine particles the same?

For the first question, if a = Rf, then Ec(i) would then be a negative value in many cases (because Rf>Ea(i) in these cases); this is obviously incorrect both in theory and in practice. The author's opinon is that there is no theoretical or practical reason why this by-pass fraction, a, should equal the water split to the underflow, Rf, under all circumstances.

Luckie and Austin (58) have reviewed the methods of analysis of classifier data and outlined a sophisticated mathematical procedure for fitting an appropriate function to the performance curve. Recently Austin and Klimpel (41) have suggested a mathematical procedure for obtaining the complete performance curve based on extrapolation of the smaller sizes of the feed size distribution on a Schuhmann plot, and fitting the performance curve to a three-parameter function (by-pass, d50c and steepness parameters). The work in this study was undertaken to find another way to solve this problem. A relationship between the finest size fraction, Fz(% -53 microns reporting to the sands) and the operating variables has been investigated, and a regression equation has been developed (cf. Chapter IV). The complete reduced-performance curve was obtained using Fz intead of Rf to calculate Ec(i). The advantages of this method are: 1) avoiding the unreasonable situation in which the Ec(i) is a negative value in many cases; 2) the results of using Fz to fit the test data relatively accuratey.

For the second question, the experimental results showed that the influence of entrainment on the different size fractions classified is different; that is, the influence on the coarse size fraction is less than on the fine size fraction. The principal reason is probably that the finer solids are entrained by the coarse product liquid, and solids of coarse size reporting to the sands (or the underflow) are acted upon by the gravity force. In other words, classification is dominant for coarse sizes reporting to the sands, and entrainment is dominant for fines reporting to the sands. If so, the logical conclusion is that there will probably be a critical size, Dcr, such that

$$d(i) > Dcr \qquad Ec(i) = Ea(i)$$

$$d(i) < Dcr \qquad Ec(i) = Ea(i) - a/(1-a) \qquad (6.2)$$

Where:

d(i) = particle size in the interval i in the feed

a = entrainment or by-pass fraction

Thus, the main problem becomes how to determine Dcr and a. If these two parameters can be found, a more accurate Ec could then be obtained. However, this work is beyond the scope of this thesis.

### 6.2.2 Fitting the Equation For the Reduced-Performance Curve

In this study Equation 2.4 was used to present the reduced-performance curve:

$$Ec = 1 - (-0.693(d/d50c)^{m}) \qquad (2.4)$$

Where m embodies all of the variables affecting the sharpness of separation. The value of m varies between 1.5 to 3.5 for hydrocyclones (10), and between 1.0 to 2.5 for the spiral classifier (see Chapter III).

The regression Equation 4.4 indicates that most of the variables which affect the value of m are operating variables, and among them the size distribution of the feed is the most important factor. As the goodness-of-fit is different in the different sections of the reduced-performance curve, the best way to improve the goodness-of-fit would probably be to fit according to the different sections of the curve, i.e., divide the reduced-performance curve into several (2 or 3) sections, with each section fitted using a different value of m.

### 6.2.3 Methods to Determine d50c

Altogether four methods were used to determine d50c in this study: 1) The Lagrange interpolation method; 2) The linear interpolation (two-point interpolation) method; 3) Calculation from slope, m, of the reduced-performance curve; and 4) Direct determination from the reduced-performace curve. The calculated results are given in Appendix III.1.

Only a few experimental data would be included using the straight line method. The method of direct determination of d50c from the reduced-performance curve is very simple, but it is not convenient when using the computer. It seems to be that the Lagrange interception method is better because more test data can be used, and more accurate results could be obtained when adopting computer calculation. The third method, using slope, m of the reduced-performance curve to calculate d50c would also be a good method if the goodness-of-fit of the reduced-performance curve was improved and the value of m was sufficiently accurate.

### 6.3 Simulation of Grinding-classifying Circuit

The simulation of a closed grinding circuit which consists of a ball mill and a spiral classifier has been carried out using a plug flow ball mill model and the spiral classifier model developed in this study. The major objective was to examine the application and suitability of the model developed for the simulation of grinding-classifying circuits. Although the simulation results are basically satisfactory, some aspects still need to be improved.

### 6.3.1 Grinding

The simulation subroutine of a ball mill requires information on the feed rate and sizing analysis of the ore entering the mill as well as values for the breakage rate, and the mill parameters, such as the diameter and length of the mill, ball load, critical speed, the throughput of the mill, etc. Although the simulation program included most of the above information, some were not considered in the plug flow model.

When carrying out simulation on a computer, it is of considerable importance to relate simulation results to practical operating behavior. Operating equipment has certain physical limitations which define the limits of performance. Ball mills are restricted to a certain maximum throughput, beyond which the mill discharges part of its ball load if it is an overflow mill, or fills up if it is a grate mill. If the predicted flow rate is beyond the practical limitations of the ball mill then the simulation is invalid. In order to increase the accuracy of simulation, it may be necessary to find other models, for example, the population balance model.

### 6.3.2 Classification

The mathematical model for the spiral classifier which was used in the simulation of the grinding-classifying circuit included all operating and design variables excepting the screw speed. It has been demonstrateed that this model is suitable for simulation under certain conditions. Only a single mineral (dolomite) was tested, and small equipment was used in all the tests by which the spiral classifier model was developed.

## 6.4 Further Work

1. To study the influence of entrainment on the different size fractions and find a more accurate method to determine the reduced-performance curve.

2. To firmly establish the relationship between sharpness of separation and the operating and design variables of a spiral classifier because of the poor correlation coefficient obtained in Equation 4.4. Try using different values of m to fit the different sections of the reduced-performance curve.

3. To study classification of mixtures of minerals by doing experimental work or collecting plant data which are suitable for investigating aspects of the classification behavior of mixtures of minerals.

4. To develop a scale-up procedure so that the mathematical model of the spiral classifier which was formulated in this study can be used to predict the

performance of spiral classifiers over a wide range of sizes and operating conditions.

# CHAPTER VII

## CONCLUSIONS

The conclusions of this study are summarized as follows:

1. A mathematical model of a spiral classifier has been developed based on the concept of d50c and the reduced-performance curve.

2. The model which has been formulated enables the performance of a spiral classifier to be calculated with reasonable accuracy when operating and design variables are available.

3. The equations clearly reveal the independent effects and relative importance of all the major variables which influence the operation of a spiral classifier.

4. There is no theoretical or practical reason why the by-pass fraction (without classification) should equal the water split to the sands under all circumstances. For a mspiral classifier, the best method to calculate the corrected performance is by use of the finest size fraction instead of the water split to the sand. As the influence of entrainment on the different size fractions in the classifier varies, further experimental work is required to find a more accurate method for calculating the corrected

performance.

5. The reduced-performance curve for a mineral in a classifier is basically constant irrespective of the operating conditions.

6. More work is required to firmly establish the relationship between the sharpness of separation and the operating and design variables of a spiral classifier. A method by which different values of "m" are used to fit the different sections of the reduced-performance curve may give a more accurate result.

7. The model developed in this thesis, combined with a ball mill model can be used for simulation of closed circuit grinding.

8. Further work is required before it is possible to use this model for classification of ores and for large scale equipment.

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# APPENDIX I

## RESULTS OF EACH TEST

Table AI.1 Results of Test NO.1

| Size (Micr.) | Size Distribution (%) O/F | Sand | Cal.F | Mea.F | Ea (%) | Ec (%) |
|---|---|---|---|---|---|---|
| 2803 | 0.00 | 0.04 | 0.02 | 0.01 | 100.00 | 100.00 |
| 992 | 1.36 | 42.83 | 23.33 | 22.81 | 97.26 | 96.90 |
| 350 | 1.36 | 21.32 | 11.93 | 11.51 | 94.64 | 93.94 |
| 248 | 4.77 | 12.34 | 8.78 | 8.80 | 74.46 | 71.10 |
| 174 | 3.07 | 7.48 | 5.41 | 5.40 | 73.30 | 69.79 |
| 104 | 2.05 | 1.57 | 1.80 | 2.07 | 46.32 | 39.27 |
| 63 | 23.85 | 7.01 | 14.93 | 14.88 | 24.88 | 15.01 |
| -63 | 63.54 | 7.41 | 33.80 | 34.52 | 11.61 | 0.00 |

RF=10.5993951 OFW=2.98 SW=3.36

Table AI.2 Results of Test No.2

| Size | | Size Distribution (%) | | | EA | EC |
|---|---|---|---|---|---|---|
| Micr. | O/F | SAND | CAL.F | Mea.F | % | % |
| 2803 | 0.00 | 0.04 | 0.02 | 0.01 | 100.00 | 100.00 |
| 992 | 4.13 | 43.50 | 22.39 | 22.47 | 90.11 | 89.10 |
| 350 | 2.07 | 19.94 | 10.36 | 10.40 | 89.28 | 88.19 |
| 248 | 4.29 | 12.60 | 8.14 | 7.92 | 71.76 | 68.86 |
| 174 | 3.96 | 8.03 | 5.85 | 5.28 | 63.69 | 59.97 |
| 104 | 15.85 | 5.98 | 11.27 | 11.32 | 24.61 | 16.88 |
| 63 | 9.76 | 2.81 | 6.54 | 6.18 | 19.94 | 11.74 |
| -63 | 59.94 | 7.10 | 35.43 | 36.42 | 9.29 | 0.00 |

RF=8.43357568 OFW=3.29 SW=2.85

Table AI.3 Results of Test No.3

| Size Micr. | O/F | SAND | CAL.F | Mea.F | EA % | EC % |
|---|---|---|---|---|---|---|
| 2803 | 0.00 | 0.03 | 0.01 | 0.01 | 100.00 | 100.00 |
| 992 | 0.84 | 42.28 | 20.46 | 20.52 | 97.84 | 97.61 |
| 350 | 1.34 | 21.73 | 10.99 | 10.37 | 93.58 | 92.89 |
| 248 | 4.19 | 12.74 | 8.24 | 8.63 | 73.22 | 70.34 |
| 174 | 5.36 | 7.59 | 6.42 | 6.95 | 56.01 | 51.28 |
| 104 | 5.01 | 3.68 | 4.38 | 4.17 | 39.78 | 33.30 |
| 63 | 20.45 | 4.43 | 12.86 | 12.35 | 16.30 | 7.29 |
| -63 | 62.81 | 7.52 | 36.63 | 37.00 | 9.72 | 0.00 |

(Size Distribution (%) spans O/F, SAND, CAL.F, Mea.F)

RF=9.21607195 OFW=3.17 SW=2.85

Table AI.4 Results of Test No.4

| Size Micr. | O/F | Size Distribution (%) SAND | CAL.F | Mea.F | EA % | EC % |
|---|---|---|---|---|---|---|
| 2308 | 0.00 | 0.03 | 0.02 | 0.03 | 100.00 | 100.00 |
| 992 | 2.64 | 32.02 | 23.37 | 23.81 | 96.67 | 94.55 |
| 350 | 2.64 | 16.64 | 12.52 | 12.23 | 93.79 | 89.82 |
| 248 | 6.61 | 12.86 | 11.02 | 10.99 | 82.33 | 71.04 |
| 174 | 4.41 | 7.52 | 6.60 | 7.09 | 80.33 | 67.76 |
| 104 | 4.64 | 4.45 | 4.51 | 4.56 | 69.67 | 50.28 |
| 63 | 20.47 | 10.84 | 13.68 | 13.43 | 55.92 | 27.73 |
| -63 | 58.59 | 15.64 | 28.29 | 27.68 | 39.00 | 0.00 |

RF=54.604727 OFW=1.63 SW=3.90

Table AI.5 Results of Test No.5

| Size | Size Distribution (%) | | | | EA | EC |
|---|---|---|---|---|---|---|
| Micr. | O/F | SAND | CAL.F | Mea.F | % | % |
| 2803 | 0.00 | 0.09 | 0.06 | 0.00 | 100.00 | 100.00 |
| 992 | 2.48 | 30.16 | 22.46 | 21.63 | 96.93 | 94.32 |
| 350 | 2.27 | 16.27 | 12.38 | 12.52 | 94.90 | 90.57 |
| 248 | 8.19 | 14.27 | 12.58 | 11.98 | 81.89 | 66.53 |
| 174 | 6.49 | 7.76 | 7.41 | 7.55 | 75.63 | 54.95 |
| 104 | 4.89 | 4.18 | 4.38 | 4.95 | 68.93 | 42.57 |
| 63 | 20.93 | 9.37 | 12.59 | 12.41 | 53.75 | 14.50 |
| -63 | 54.75 | 17.90 | 28.15 | 28.96 | 45.90 | 0.00 |

RF=47.9145678 OFW=1.49 SW=3.87

Table AI.6 Results of Test No.6

| Size | Size Distribution (%) | | | | EA | EC |
|---|---|---|---|---|---|---|
| Micr. | O/F | SAND | CAL.F | Mea.F | % | % |
| 2803 | 0.00 | 0.08 | 0.06 | 0.00 | 100.00 | 100.00 |
| 992 | 3.08 | 34.24 | 25.46 | 25.09 | 96.59 | 94.02 |
| 350 | 5.68 | 16.63 | 13.55 | 13.07 | 88.19 | 79.26 |
| 248 | 6.77 | 14.63 | 12.42 | 12.68 | 84.64 | 73.02 |
| 174 | 5.89 | 5.75 | 5.79 | 5.29 | 71.35 | 49.67 |
| 104 | 9.01 | 7.25 | 7.75 | 8.14 | 67.24 | 42.45 |
| 63 | 18.43 | 6.25 | 9.68 | 9.07 | 46.38 | 5.81 |
| -63 | 51.14 | 15.17 | 25.30 | 26.66 | 43.07 | 0.00 |

RF=38.8530821 OFW=1.59 SW=4.05

Table AI.7 Results of Test No.7

| Size | Size Distribution (%) | | | | EA | EC |
|---|---|---|---|---|---|---|
| Micr. | O/F | SAND | CAL.F | Mea.F | % | % |
| 2803 | 0.00 | 0.26 | 0.12 | 0.17 | 100.00 | 100.00 |
| 992 | 2.46 | 66.86 | 32.99 | 32.17 | 96.08 | 95.73 |
| 350 | 4.57 | 11.41 | 7.81 | 7.41 | 69.24 | 66.53 |
| 248 | 8.26 | 8.38 | 8.32 | 8.62 | 47.77 | 43.16 |
| 174 | 4.82 | 3.52 | 4.20 | 4.80 | 39.70 | 34.38 |
| 104 | 8.92 | 2.56 | 5.90 | 5.11 | 20.55 | 13.55 |
| 63 | 23.32 | 2.35 | 13.38 | 16.58 | 8.33 | 0.25 |
| -63 | 47.65 | 4.66 | 27.27 | 25.14 | 8.10 | 0.00 |

RF=7.90602395 OFW=7.02 SW=6.33

Table AI.8 Results of Test No.8

| Size | | Size Distribution (%) | | | EA | EC |
|---|---|---|---|---|---|---|
| Micr. | O/F | SAND | CAL.F | Mea.F | % | % |
| 2803 | 0.00 | 0.16 | 0.08 | 0.10 | 100.00 | 100.00 |
| 992 | 1.22 | 61.76 | 32.07 | 32.14 | 98.13 | 97.87 |
| 350 | 2.48 | 11.42 | 7.04 | 7.47 | 82.71 | 80.31 |
| 248 | 5.90 | 7.96 | 6.95 | 6.96 | 58.36 | 52.57 |
| 174 | 7.79 | 4.22 | 6.09 | 6.56 | 35.49 | 26.51 |
| 104 | 3.59 | 1.47 | 2.51 | 2.62 | 29.85 | 20.09 |
| 63 | 24.84 | 5.78 | 15.13 | 14.98 | 19.47 | 8.27 |
| -63 | 54.00 | 7.23 | 30.17 | 29.17 | 12.21 | o.00 |

RF=9.33190906 OFW=3.30 SW=3.43

Table AI.9 Results of Test No.9

| Size | Size Distribution (%) | | | | EA | EC |
|---|---|---|---|---|---|---|
| Micr. | O/F | SAND | CAL.F | Mea.F | % | % |
| 2803 | 0.00 | 0.97 | 0.55 | 0.60 | 100.00 | 100.00 |
| 992 | 2.43 | 65.15 | 37.71 | 38.10 | 97.18 | 96.50 |
| 350 | 4.96 | 9.68 | 7.61 | 7.29 | 71.50 | 64.65 |
| 248 | 7.61 | 5.32 | 6.32 | 6.60 | 47.33 | 34.68 |
| 174 | 8.49 | 4.23 | 6.09 | 6.20 | 39.04 | 24.40 |
| 104 | 4.09 | 0.97 | 2.34 | 2.72 | 23.36 | 4.96 |
| 63 | 21.14 | 4.10 | 11.56 | 11.14 | 19.95 | 0.73 |
| -63 | 51.28 | 9.58 | 27.83 | 27.35 | 19.36 | 0.00 |

RF=23.0467045 OFW=4.45 SW=5.72

Table AI.10 Results of Test No.10

| Size | Size Distribution (%) | | | | EA | EC |
|---|---|---|---|---|---|---|
| Micr. | O/F | SAND | CAL.F | Mea.F | % | % |
| 2803 | 0.00 | 0.09 | 0.05 | 0.05 | 100.00 | 100.00 |
| 992 | 5.42 | 48.12 | 28.59 | 28.69 | 91.33 | 88.08 |
| 350 | 6.90 | 10.51 | 8.86 | 8.76 | 64.38 | 51.04 |
| 248 | 8.25 | 8.85 | 8.58 | 8.14 | 56.00 | 39.53 |
| 174 | 8.25 | 7.63 | 7.91 | 7.85 | 52.32 | 34.47 |
| 104 | 5.48 | 3.64 | 4.48 | 4.38 | 44.07 | 23.14 |
| 63 | 19.39 | 6.55 | 12.42 | 12.71 | 28.61 | 1.89 |
| -63 | 46.31 | 14.61 | 29.11 | 29.42 | 27.24 | 0.00 |

RF=35.917768 OFW=4.36 SW=5.18

Table AI.11 Results of Test No.11

| Size | Size Distribution (%) | | | | EA | EC |
|---|---|---|---|---|---|---|
| Micr. | O/F | SAND | CAL.F | Mea.F | % | % |
| 2803 | 0.00 | 0.09 | 0.05 | 0.07 | 100.00 | 100.00 |
| 992 | 3.70 | 54.01 | 33.56 | 34.05 | 95.52 | 93.77 |
| 350 | 6.17 | 10.58 | 8.79 | 8.61 | 71.46 | 60.31 |
| 248 | 7.27 | 7.11 | 7.18 | 7.84 | 58.81 | 42.73 |
| 174 | 6.02 | 5.11 | 5.48 | 5.07 | 55.34 | 37.91 |
| 104 | 5.11 | 3.55 | 4.18 | 4.21 | 50.36 | 30.97 |
| 63 | 22.56 | 6.40 | 12.97 | 12.66 | 29.29 | 1.68 |
| -63 | 49.17 | 13.15 | 27.79 | 27.49 | 28.08 | 0.00 |

RF=26.7848196 OFW=3.64 SW=5.31

Table AI.12 Results of Test No.12

| Size | Size Distribution (%) | | | | EA | EC |
|---|---|---|---|---|---|---|
| Micr. | O/F | SAND | CAL.F | Mea.F | % | % |
| 2803 | 0.00 | 0.10 | 0.05 | 0.03 | 100.00 | 100.00 |
| 992 | 6.15 | 50.93 | 28.28 | 28.10 | 89.00 | 84.73 |
| 350 | 7.92 | 10.14 | 9.02 | 9.04 | 55.58 | 38.30 |
| 248 | 10.53 | 6.55 | 8.56 | 8.89 | 37.81 | 13.62 |
| 174 | 8.97 | 4.62 | 6.82 | 6.36 | 33.48 | 7.61 |
| 104 | 13.50 | 6.20 | 9.89 | 9.43 | 30.98 | 4.14 |
| 63 | 12.37 | 5.32 | 8.89 | 9.42 | 29.59 | 2.21 |
| -63 | 40.56 | 16.14 | 28.49 | 28.93 | 28.00 | 0.00 |

RF=21.0211841 OFW=7.38 SW=7.21

Table AI.13 Results of Tests No.13

| Size | Size Distribution (%) | | | | Ea | Ec |
|---|---|---|---|---|---|---|
| Micr. | O/F | SAND | CAL.F | Mea.F | % | % |
| 2803 | 0.00 | 0.08 | 0.04 | 0.06 | 100.00 | 100.00 |
| 992 | 5.99 | 41.14 | 23.85 | 23.61 | 87.65 | 82.11 |
| 350 | 8.03 | 12.30 | 10.20 | 10.79 | 61.28 | 43.92 |
| 248 | 10.07 | 7.73 | 8.88 | 9.13 | 44.23 | 19.22 |
| 174 | 9.05 | 6.78 | 7.79 | 8.04 | 43.63 | 18.36 |
| 104 | 19.71 | 11.05 | 15.31 | 15.66 | 36.68 | 8.28 |
| 63 | 5.86 | 3.00 | 4.41 | 4.28 | 34.60 | 5.27 |
| -63 | 41.29 | 17.92 | 29.41 | 28.43 | 30.96 | 0.00 |

RF=23.7076052 OFW=6.51 SW=6.72

Table AI.14 Results of Test No.14

| Size | Size Distribution (%) | | | | EA | EC |
|---|---|---|---|---|---|---|
| Micr. | O/F | SAND | CAL.F | Mea.F | % | % |
| 2803 | 0.00 | 1.31 | 0.12 | 0.15 | 100.00 | 100.00 |
| 992 | 6.95 | 66.83 | 12.63 | 12.05 | 50.20 | 49.53 |
| 350 | 6.26 | 9.88 | 6.60 | 6.43 | 14.19 | 13.05 |
| 248 | 10.60 | 5.60 | 10.13 | 10.40 | 5.25 | 3.98 |
| 174 | 9.05 | 3.93 | 8.56 | 8.86 | 4.35 | 3.07 |
| 104 | 16.68 | 4.93 | 15.57 | 15.78 | 3.00 | 1.71 |
| 63 | 8.12 | 2.12 | 7.55 | 7.37 | 2.66 | 1.36 |
| -63 | 42.34 | 5.40 | 38.84 | 38.87 | 1.32 | 0.00 |

RF=2.41971959 OFW=10.93 SW=1.15

Table AI.15 Results of Test No.15

| Size | Size Distribution (%) | | | | EA | EC |
|---|---|---|---|---|---|---|
| Micr. | O/F | AND | CAL.F | Mea.F | % | % |
| 2803 | 0.00 | 0.20 | 0.02 | 0.03 | 100.00 | 100.00 |
| 992 | 7.67 | 64.40 | 13.03 | 13.20 | 46.69 | 45.73 |
| 350 | 8.23 | 11.64 | 8.55 | 8.58 | 12.86 | 11.28 |
| 248 | 11.31 | 6.26 | 10.83 | 10.42 | 5.46 | 3.74 |
| 174 | 9.79 | 4.07 | 9.25 | 8.99 | 4.16 | 2.42 |
| 104 | 11.27 | 3.42 | 10.53 | 10.23 | 3.07 | 1.31 |
| 63 | 8.92 | 2.57 | 8.32 | 8.62 | 2.92 | 1.16 |
| -63 | 42.81 | 7.44 | 39.47 | 39.93 | 1.78 | 0.00 |

RF=2.05230528 OFW=10.42 SW=1.09

Table AI.16 Results of Test No.16

| Size | Size Distribution (%) | | | | EA | EC |
|---|---|---|---|---|---|---|
| Micr. | O/F | SAND | CAL.F | Mea.F | % | % |
| 2803 | 0.00 | 0.24 | 0.12 | 0.12 | 100.00 | 100.00 |
| 992 | 3.70 | 71.39 | 38.43 | 38.68 | 95.31 | 94.55 |
| 350 | 8.62 | 9.66 | 9.15 | 9.79 | 54.14 | 46.73 |
| 248 | 9.50 | 5.51 | 7.45 | 7.24 | 37.93 | 27.89 |
| 174 | 10.41 | 2.44 | 6.32 | 6.31 | 19.80 | 6.83 |
| 104 | 16.46 | 2.82 | 9.46 | 10.09 | 15.29 | 1.59 |
| 63 | 7.27 | 1.18 | 4.15 | 4.05 | 14.60 | 0.79 |
| -63 | 44.07 | 6.76 | 24.91 | 23.72 | 13.92 | 0.00 |

RF=18.7776492 OFW=4.15 SW=4.37

Table AI.17 Results of Test No.17

| Size | Size Distribution (%) | | | | EA | EC |
|---|---|---|---|---|---|---|
| Micr. | O/F | SAND | CAL.F | Mea.F | % | % |
| 2803 | 0.00 | 0.41 | 0.22 | 0.24 | 100.00 | 100.00 |
| 992 | 5.22 | 70.73 | 40.53 | 40.27 | 94.06 | 92.85 |
| 350 | 9.38 | 8.50 | 8.91 | 9.53 | 51.44 | 41.52 |
| 248 | 10.85 | 4.46 | 7.41 | 7.91 | 32.46 | 18.65 |
| 174 | 9.30 | 2.54 | 5.66 | 5.23 | 24.20 | 8.71 |
| 104 | 21.78 | 5.32 | 12.91 | 12.98 | 22.21 | 6.31 |
| 63 | 7.38 | 1.73 | 4.33 | 4.54 | 21.51 | 5.47 |
| -63 | 36.09 | 6.31 | 20.04 | 19.30 | 16.97 | 0.00 |

RF=20.0867247 OFW=4.04 SW=4.72

Table AI.18 Results of Test No.18

| Size | Size Distribution (%) | | | | EA | EC |
|---|---|---|---|---|---|---|
| Micr. | O/F | SAND | CAL.F | Mea.F | % | % |
| 2803 | 0.00 | 0.20 | 0.05 | 0.06 | 100.00 | 100.00 |
| 992 | 6.52 | 60.86 | 19.41 | 20.18 | 74.38 | 72.91 |
| 350 | 7.69 | 10.26 | 8.30 | 8.78 | 29.33 | 25.25 |
| 248 | 10.11 | 6.76 | 9.32 | 9.14 | 17.22 | 12.44 |
| 174 | 7.85 | 4.94 | 7.16 | 7.47 | 16.37 | 11.55 |
| 104 | 24.23 | 8.23 | 20.43 | 19.82 | 9.56 | 4.34 |
| 63 | 7.85 | 2.12 | 6.49 | 6.56 | 7.75 | 2.43 |
| -63 | 35.75 | 6.63 | 28.84 | 27.99 | 5.45 | 0.00 |

RF=10.318997 OFW=8.48 SW=2.64

Table AI.19 Results of Test No.19

| Size | Size Distribution (%) | | | | EA | EC |
|---|---|---|---|---|---|---|
| Micr. | O/F | SAND | CAL.F | Mea.F | % | % |
| 2083 | 0.00 | 0.16 | 0.06 | 0.05 | 100.00 | 100.00 |
| 992 | 4.79 | 67.89 | 29.85 | 29.94 | 90.33 | 89.38 |
| 350 | 7.07 | 10.50 | 8.43 | 9.02 | 49.46 | 44.48 |
| 248 | 9.88 | 5.15 | 8.00 | 7.69 | 25.57 | 18.23 |
| 174 | 8.71 | 3.78 | 6.75 | 6.65 | 22.24 | 14.57 |
| 104 | 17.16 | 4.10 | 11.97 | 11.24 | 13.60 | 5.09 |
| 63 | 13.36 | 3.03 | 11.07 | 11.81 | 10.88 | 2.09 |
| -63 | 36.03 | 5.39 | 23.86 | 23.60 | 8.97 | 0.00 |

RF=8.1601994 OFW=6.18 SW=4.08

Table AI.20 Results of Test No.20

| Size | Size Distribution (%) | | | | EA | EC |
|---|---|---|---|---|---|---|
| Micr. | O/F | SAND | CAL.F | Mea.F | % | % |
| 2803 | 0.00 | 0.17 | 0.04 | 0.03 | 100.00 | 100.00 |
| 992 | 7.15 | 70.71 | 21.96 | 21.22 | 75.02 | 74.01 |
| 350 | 7.82 | 10.76 | 8.50 | 9.04 | 29.47 | 26.62 |
| 248 | 10.86 | 5.31 | 9.57 | 9.32 | 12.93 | 9.40 |
| 174 | 9.57 | 2.73 | 7.98 | 7.76 | 7.97 | 4.25 |
| 104 | 20.24 | 4.33 | 16.53 | 17.74 | 6.10 | 2.30 |
| 63 | 6.87 | 0.99 | 5.50 | 4.58 | 4.19 | 0.31 |
| -63 | 37.49 | 5.00 | 29.72 | 30.26 | 3.89 | 0.00 |

RF=4.71531292 OFW=12.95 SW=3.93

Table AI.21 Results of Test No.21

| Size | Size Distribution (%) | | | | EA | EC |
|---|---|---|---|---|---|---|
| Micr. | O/F | SAND | CAL.F | Mea.F | % | % |
| 2803 | 0.00 | 0.37 | 0.04 | 0.04 | 100.00 | 100.00 |
| 992 | 4.61 | 72.46 | 11.40 | 11.50 | 63.60 | 63.04 |
| 350 | 6.11 | 9.61 | 6.46 | 6.18 | 14.88 | 13.57 |
| 248 | 7.55 | 3.94 | 7.19 | 7.22 | 5.48 | 4.02 |
| 174 | 7.70 | 2.39 | 7.17 | 7.98 | 3.33 | 1.84 |
| 104 | 23.75 | 4.31 | 21.81 | 21.29 | 1.98 | 0.47 |
| 63 | 9.78 | 1.48 | 8.95 | 8.42 | 1.65 | 0.14 |
| -63 | 40.50 | 5.62 | 37.01 | 37.37 | 1.52 | 0.00 |

RF=2.84710703 OFW=12.91 SW=1.43

Table AI.22 Results of Test No.22

| Size Micr. | Size Distribution (%) O/F | SAND | CAL.F | Mea.F | EA % | EC % |
|---|---|---|---|---|---|---|
| 2803 | 0.00 | 0.36 | 0.04 | 0.03 | 100.00 | 100.00 |
| 992 | 3.80 | 70.99 | 10.70 | 10.25 | 68.15 | 67.53 |
| 350 | 5.47 | 7.03 | 5.63 | 6.02 | 12.83 | 11.15 |
| 248 | 9.04 | 5.60 | 8.69 | 9.03 | 6.62 | 4.83 |
| 174 | 8.68 | 2.34 | 8.03 | 8.29 | 2.99 | 1.13 |
| 104 | 24.32 | 5.25 | 22.36 | 22.51 | 2.41 | 0.54 |
| 63 | 9.07 | 1.78 | 8.32 | 8.74 | 2.20 | 0.32 |
| -63 | 39.62 | 6.65 | 36.63 | 35.08 | 1.89 | 0.00 |

RF=2.93086719 OFW=13.36 SW=1.53

Table AI.23 Results of Test No.23

| Size | Size Distribution (%) | | | | EA | EC |
|---|---|---|---|---|---|---|
| Micr. | O/F | SAND | CAL.F | Mea.F | % | % |
| 2803 | 0.00 | 0.09 | 0.04 | 0.05 | 100.00 | 100.00 |
| 992 | 2.41 | 31.91 | 15.36 | 15.06 | 91.19 | 87.83 |
| 350 | 6.48 | 12.00 | 8.90 | 8.97 | 59.15 | 43.54 |
| 248 | 9.02 | 7.44 | 8.33 | 8.87 | 39.21 | 15.98 |
| 174 | 8.48 | 6.51 | 7.62 | 7.16 | 37.51 | 13.63 |
| 104 | 22.28 | 15.13 | 19.14 | 19.54 | 34.69 | 9.72 |
| 63 | 9.77 | 6.26 | 8.23 | 8.06 | 33.38 | 7.92 |
| -63 | 42.27 | 20.66 | 32.79 | 32.29 | 27.65 | 0.00 |

RF=27.4128544 OFW=7.13 SW=5.58

Table AI.24 Results of Test No.24

| Size | Size Distribution (%) | | | | EA | EC |
|---|---|---|---|---|---|---|
| Micr. | O/F | SAND | CAL.F | Mea.F | % | % |
| 2803 | 0.00 | 0.19 | 0.07 | 0.06 | 100.00 | 100.00 |
| 992 | 3.36 | 49.51 | 20.35 | 20.56 | 89.56 | 87.73 |
| 350 | 6.52 | 13.49 | 9.09 | 9.98 | 54.65 | 46.67 |
| 248 | 7.32 | 6.56 | 7.04 | 7.33 | 34.29 | 22.73 |
| 174 | 11.10 | 4.79 | 8.78 | 8.49 | 20.08 | 6.02 |
| 104 | 25.32 | 10.54 | 19.88 | 19.96 | 19.51 | 5.35 |
| 63 | 11.04 | 4.24 | 8.54 | 8.91 | 18.28 | 3.90 |
| -63 | 35.34 | 10.68 | 26.26 | 24.71 | 14.97 | 0.00 |

RF=21.9503176 OFW=8.95 SW=5.21

Table AI.25 Results of Test No.25

| Size | | Size Distribution (%) | | | EA | EC |
|---|---|---|---|---|---|---|
| Micr. | O/F | SAND | CAL.F | Mea.F | % | % |
| 2803 | 0.00 | 0.42 | 0.04 | 0.03 | 100.00 | 100.00 |
| 992 | 3.34 | 75.88 | 9.60 | 9.71 | 68.23 | 67.91 |
| 350 | 4.44 | 9.27 | 4.86 | 5.06 | 16.48 | 15.65 |
| 248 | 9.13 | 3.85 | 8.67 | 8.67 | 3.83 | 2.88 |
| 174 | 8.70 | 2.05 | 8.13 | 7.94 | 2.18 | 1.21 |
| 104 | 25.07 | 3.25 | 23.19 | 23.09 | 1.21 | 0.23 |
| 63 | 10.59 | 1.21 | 9.78 | 9.27 | 1.07 | 0.09 |
| -63 | 38.73 | 4.07 | 35.74 | 36.23 | 0.98 | 0.00 |

RF=2.30280032 OFW=13.20 SW=1.25

Table AI.26 Results of Test No.26

| Size | | Size Distribution (%) | | | EA | EC |
|---|---|---|---|---|---|---|
| Micr. | O/F | SAND | CAL.F | Mea.F | % | % |
| 2803 | 0.00 | 0.42 | 0.03 | 0.04 | 100.00 | 100.00 |
| 992 | 3.10 | 76.32 | 8.63 | 8.70 | 66.78 | 66.48 |
| 350 | 4.05 | 7.06 | 4.28 | 4.08 | 12.46 | 11.66 |
| 248 | 8.86 | 3.83 | 8.48 | 8.35 | 3.41 | 2.53 |
| 174 | 10.86 | 2.12 | 10.20 | 10.52 | 1.57 | 0.67 |
| 104 | 23.37 | 4.15 | 21.92 | 21.36 | 1.43 | 0.53 |
| 63 | 13.84 | 1.90 | 12.94 | 12.48 | 1.11 | 0.20 |
| -63 | 35.92 | 4.02 | 33.51 | 34.47 | 0.91 | 0.00 |

RF=1.91358719 OFW=11.20 SW=0.91

Table AI.27 Results of Test No.27

| Size | Size Distribution (%) | | | | EA | EC |
|---|---|---|---|---|---|---|
| Micr. | O/F | SAND | CAL.F | Ea.F | % | % |
| 2803 | 0.00 | 0.39 | 0.02 | 0.03 | 100.00 | 100.00 |
| 992 | 10.34 | 56.69 | 12.47 | 12.56 | 20.86 | 19.87 |
| 350 | 8.21 | 7.69 | 8.19 | 8.34 | 4.31 | 3.12 |
| 248 | 10.30 | 6.78 | 10.14 | 10.78 | 3.07 | 1.86 |
| 174 | 9.60 | 6.10 | 9.44 | 9.31 | 2.96 | 1.76 |
| 104 | 19.31 | 9.50 | 18.86 | 19.28 | 2.31 | 1.10 |
| 63 | 5.40 | 2.38 | 5.26 | 5.09 | 2.07 | 0.86 |
| -63 | 36.84 | 9.53 | 35.59 | 34.61 | 1.23 | 0.00 |

RF=2.05591331 OFW=15.87 SW=0.763

Table AI.28 Results of Test No.28

| Size | Size Distribution (%) | | | | EA | EC |
|---|---|---|---|---|---|---|
| Micr. | O/F | SAND | CAL.F | Mea.F | % | % |
| 2803 | 0.00 | 0.14 | 0.02 | 0.02 | 100.00 | 100.00 |
| 992 | 12.63 | 40.87 | 15.83 | 15.02 | 29.23 | 24.71 |
| 350 | 8.91 | 10.83 | 9.13 | 9.73 | 13.43 | 7.90 |
| 248 | 11.03 | 8.76 | 10.77 | 11.07 | 9.21 | 3.40 |
| 174 | 9.55 | 7.41 | 9.31 | 9.03 | 9.01 | 3.20 |
| 104 | 15.00 | 10.34 | 14.47 | 14.57 | 8.09 | 2.21 |
| 63 | 5.20 | 2.78 | 4.93 | 5.03 | 6.39 | 0.40 |
| -63 | 37.68 | 18.87 | 35.55 | 35.53 | 6.01 | 0.00 |

RF=7.200653225 OFW=16.91 SW=2.16

Table AI.29 Results of Test No.29

| Size | Size Distribution (%) | | | | EA | EC |
|---|---|---|---|---|---|---|
| Micr. | O/F | SAND | CAL.F | Mea.F | % | % |
| 2803 | 0.00 | 0.13 | 0.01 | 0.02 | 100.00 | 100.00 |
| 992 | 11.33 | 47.09 | 12.83 | 12.22 | 15.41 | 13.66 |
| 350 | 9.96 | 10.05 | 9.96 | 9.57 | 4.24 | 2.25 |
| 248 | 11.25 | 7.54 | 11.09 | 11.12 | 2.85 | 0.84 |
| 174 | 8.74 | 5.07 | 8.59 | 9.01 | 2.48 | 0.46 |
| 104 | 19.56 | 11.25 | 19.21 | 19.03 | 2.46 | 0.44 |
| 63 | 6.65 | 3.51 | 6.52 | 7.02 | 2.26 | 0.24 |
| -63 | 32.51 | 15.36 | 31.79 | 32.01 | 2.03 | 0.00 |

RF=2.91794088 OFW=19.39 SW=0.85

Table AI.30 Results of Test No.30

| Size | Size Distribution (%) | | | | EA | EC |
|---|---|---|---|---|---|---|
| Micr. | O/F | SAND | CAL.F | Mea.F | % | % |
| 2803 | 0.00 | 0.20 | 0.02 | 0.01 | 100.00 | 100.00 |
| 992 | 11.03 | 45.39 | 15.28 | 15.08 | 36.77 | 32.39 |
| 350 | 9.80 | 10.30 | 9.86 | 10.01 | 12.93 | 6.90 |
| 248 | 10.73 | 7.23 | 10.30 | 10.42 | 8.69 | 2.37 |
| 174 | 9.51 | 6.04 | 9.08 | 8.98 | 8.24 | 1.88 |
| 104 | 19.04 | 11.28 | 18.08 | 18.21 | 7.73 | 1.34 |
| 63 | 1.87 | 0.93 | 1.75 | 1.81 | 6.57 | 0.10 |
| -63 | 38.02 | 18.63 | 36.62 | 35.48 | 6.48 | 0.00 |

RF=9.65136056 OFW=10.39 SW=1.47

Table AI.31 Results of Test No.31

| Size | Size Distribution (%) | | | | EA | EC |
|---|---|---|---|---|---|---|
| Micr. | O/F | SAND | CAL.F | Mea.F | % | % |
| 2803 | 0.00 | 0.24 | 0.10 | 0.10 | 100.00 | 100.00 |
| 992 | 0.11 | 62.60 | 25.80 | 25.38 | 99.75 | 99.73 |
| 350 | 0.81 | 11.99 | 5.41 | 5.28 | 91.18 | 90.48 |
| 248 | 2.14 | 6.77 | 4.04 | 4.14 | 68.83 | 66.38 |
| 174 | 3.56 | 3.81 | 3.66 | 3.94 | 42.76 | 38.27 |
| 104 | 11.81 | 4.09 | 8.64 | 8.63 | 19.47 | 13.15 |
| 63 | 6.62 | 2.08 | 4.75 | 4.03 | 17.99 | 11.55 |
| -63 | 74.95 | 8.42 | 47.60 | 48.48 | 7.27 | 0.00 |

RF=10.4242026 OFW=3.13 Sw=2.19

Table AI.32 Results of Test No.32

| Size | Size Distribution (%) | | | | EA | EC |
| --- | --- | --- | --- | --- | --- | --- |
| Micr. | O/F | SAND | CAL.F | Mea.F | % | % |
| 2803 | 0.00 | 0.07 | 0.02 | 0.02 | 100.00 | 100.00 |
| 992 | 0.23 | 55.10 | 17.08 | 17.38 | 99.07 | 99.02 |
| 350 | 1.01 | 16.12 | 5.65 | 5.03 | 87.62 | 86.99 |
| 248 | 2.57 | 8.89 | 4.51 | 4.72 | 60.53 | 58.52 |
| 174 | 4.45 | 5.36 | 4.73 | 4.59 | 34.81 | 31.50 |
| 104 | 13.65 | 5.07 | 11.01 | 10.98 | 14.14 | 9.77 |
| 63 | 7.02 | 1.24 | 5.24 | 5.30 | 7.26 | 2.55 |
| -63 | 71.07 | 8.15 | 51.74 | 51.96 | 4.84 | 0.00 |

RF=5.06616257 OFW=7.25 SW=3.22

Table AI.33 Results of Test No.33

| Size | Size Distribution (%) | | | | EA | EC |
|---|---|---|---|---|---|---|
| Micr. | O/F | SAND | CAL.F | Mea.F | % | % |
| 2803 | 0.00 | 0.04 | 0.01 | 0.01 | 100.00 | 100.00 |
| 992 | 0.17 | 53.78 | 11.31 | 11.42 | 98.81 | 98.77 |
| 350 | 1.34 | 16.84 | 4.56 | 4.16 | 76.73 | 76.05 |
| 248 | 2.94 | 9.32 | 4.27 | 4.69 | 45.40 | 43.82 |
| 174 | 4.87 | 5.64 | 5.03 | 5.09 | 23.30 | 21.08 |
| 104 | 13.87 | 5.45 | 12.12 | 11.97 | 9.34 | 6.72 |
| 63 | 7.31 | 1.25 | 6.05 | 6.09 | 4.29 | 1.52 |
| -63 | 69.50 | 7.68 | 56.65 | 56.57 | 2.82 | 0.00 |

RF=3.06098965 OFW=6.08 SW=1.60

Table AI.34 Results of Test No.34

| Size | | Size Distribution (%) | | | EA | EC |
|---|---|---|---|---|---|---|
| Micr. | O/F | SAND | CAL.F | Mea.F | % | % |
| 2803 | 0.00 | 0.05 | 0.02 | 0.00 | 100.00 | 100.00 |
| 992 | 0.14 | 31.64 | 13.26 | 13.76 | 99.38 | 99.20 |
| 350 | 1.10 | 12.32 | 5.77 | 5.75 | 88.88 | 85.62 |
| 248 | 2.74 | 8.35 | 5.08 | 4.94 | 68.50 | 59.28 |
| 174 | 4.32 | 6.21 | 5.11 | 5.50 | 50.63 | 36.19 |
| 104 | 13.36 | 8.93 | 11.52 | 12.05 | 32.29 | 12.48 |
| 63 | 7.60 | 3.49 | 5.89 | 6.15 | 24.68 | 2.64 |
| -63 | 70.74 | 29.01 | 53.36 | 51.85 | 22.64 | 0.00 |

RF=21.2157689 OFW=4.93 SW=3.52

Table AI.35 Results of Test No.35

| Size | | Size Distribution (%) | | | EA | EC |
|---|---|---|---|---|---|---|
| Micr. | O/F | SAND | CAL.F | Mea.F | % | % |
| 2803 | 0.00 | 0.03 | 0.02 | 0.03 | 100.00 | 100.00 |
| 992 | 5.12 | 22.96 | 19.81 | 19.21 | 95 43 | 80.68 |
| 350 | 4.54 | 10.29 | 9.27 | 9.45 | 91.34 | 63.40 |
| 248 | 5.98 | 5.43 | 5.53 | 5.73 | 80.87 | 19.13 |
| 174 | 6.20 | 5.36 | 5.51 | 5.29 | 80.10 | 15.87 |
| 104 | 14.10 | 11.02 | 11.56 | 11.31 | 78.44 | 8.86 |
| 63 | 6.36 | 4.91 | 5.17 | 4.99 | 78.23 | 7.98 |
| -63 | 57.70 | 40.00 | 43.13 | 43.99 | 76.34 | 0.00 |

RF=80.4888824 OFW=1.44 SW=6.68

Table AI.36 Results of Test No.36

| Size | | Size Distribution (%) | | | EA | EC |
|---|---|---|---|---|---|---|
| Micr. | O/F | SAND | CAL.F | Mea.F | % | % |
| 2803 | 0.00 | 0.09 | 0.00 | 0.01 | 100.00 | 100.00 |
| 992 | 8.60 | 52.82 | 9.82 | 10.23 | 14.82 | 13.96 |
| 350 | 6.30 | 10.79 | 6.42 | 5.98 | 4.63 | 3.66 |
| 248 | 5.56 | 4.24 | 5.52 | 5.36 | 2.12 | 1.12 |
| 174 | 5.67 | 3.24 | 5.60 | 5.66 | 1.59 | 0.59 |
| 104 | 12.20 | 6.20 | 12.03 | 12.56 | 1.42 | 0.42 |
| 63 | 5.74 | 2.51 | 5.65 | 5.56 | 1.22 | 0.22 |
| -63 | 55.93 | 20.11 | 54.94 | 54.64 | 1.01 | 0.00 |

RF=1.50530819 OFW=14.89 SW=0.42

Table AI.37 Results of Test No.37

| Size | Size Distribution (%) | | | | EA | EC |
|---|---|---|---|---|---|---|
| Micr. | O/F | SAND | CAL.F | Mea.F | % | % |
| 2803 | 0.00 | 0.07 | 0.01 | 0.04 | 100.00 | 100.00 |
| 992 | 11.16 | 34.98 | 13.24 | 12.48 | 23.06 | 18.67 |
| 350 | 6.01 | 11.20 | 6.46 | 5.99 | 15.13 | 10.29 |
| 248 | 5.20 | 5.15 | 5.20 | 5.51 | 8.65 | 3.44 |
| 174 | 5.56 | 4.40 | 5.46 | 5.47 | 7.04 | 1.73 |
| 104 | 12.28 | 8.32 | 11.93 | 12.20 | 6.08 | 0.73 |
| 63 | 5.92 | 3.76 | 5.73 | 5.34 | 5.73 | 0.35 |
| -63 | 53.87 | 32.12 | 51.97 | 52.97 | 5.39 | 0.00 |

RF=6.42023347 OFW=8.23 SW=0.79

Table AI.38 Results of Test No.38

| Size | Size Distribution (%) | | | | EA | EC |
|---|---|---|---|---|---|---|
| Micr. | O/F | SAND | CAL.F | Mea.F | % | % |
| 2803 | 0.00 | 0.04 | 0.00 | 0.05 | 100.00 | 100.00 |
| 992 | 10.60 | 35.04 | 13.49 | 12.60 | 30.68 | 25.18 |
| 350 | 6.09 | 10.27 | 6.58 | 6.00 | 18.42 | 11.95 |
| 248 | 5.48 | 5.26 | 5.45 | 5.63 | 11.39 | 4.36 |
| 174 | 5.65 | 4.57 | 5.52 | 5.54 | 9.77 | 2.61 |
| 104 | 12.26 | 8.85 | 11.86 | 12.01 | 8.81 | 1.58 |
| 63 | 5.69 | 3.84 | 5.47 | 5.40 | 8.29 | 1.01 |
| -63 | 54.23 | 32.13 | 51.62 | 52.77 | 7.35 | 0.00 |

RF=8.6359737 OFW=7.84 SW=1.05

Table AI.39 Results of Test No.39

| Size | Size Distribution (%) | | | | EA | EC |
|---|---|---|---|---|---|---|
| Micr. | O/F | SAND | CAL.F | Mea.F | % | % |
| 2803 | 0.00 | 0.06 | 0.02 | 0.00 | 100.00 | 100.00 |
| 992 | 1.19 | 62.80 | 18.27 | 17.24 | 95.29 | 94.98 |
| 350 | 2.88 | 12.20 | 5.46 | 5.76 | 61.91 | 59.41 |
| 248 | 3.90 | 5.27 | 4.28 | 4.19 | 34.14 | 29.82 |
| 174 | 4.57 | 3.04 | 4.15 | 4.48 | 20.33 | 15.11 |
| 104 | 12.12 | 3.66 | 9.77 | 10.24 | 10.38 | 4.51 |
| 63 | 6.44 | 1.20 | 4.99 | 5.02 | 6.67 | 0.56 |
| -63 | 68.90 | 11.77 | 53.06 | 53.07 | 6.15 | 0.00 |

rf=7.26012954 OFW=7.54 SW=2.89

Table AI.40 Results of Test No.40

| Size | Size Distribution (%) | | | | EA | EC |
|---|---|---|---|---|---|---|
| Micr. | O/F | SAND | CAL.F | Mea.F | % | % |
| 2803 | 0.00 | 0.18 | 0.01 | 0.07 | 100.00 | 100.00 |
| 992 | 3.38 | 60.26 | 7.31 | 7..91 | 56.99 | 56.26 |
| 350 | 4.47 | 10.64 | 4.90 | 4.90 | 15.03 | 13.59 |
| 248 | 4.34 | 5.07 | 4.39 | 4.51 | 7.99 | 6.43 |
| 174 | 4.95 | 3.21 | 4.74 | 4.74 | 4.69 | 3.07 |
| 104 | 11.82 | 4.19 | 11.29 | 11.07 | 2.57 | 0.91 |
| 63 | 6.20 | 1.62 | 5.88 | 5.85 | 1.90 | 0.24 |
| -63 | 64.94 | 14.83 | 61.47 | 60.95 | 1.67 | 0.00 |

RF=2.48264816 OFW=15.23 SW=1.13

Table AI.41 Results of Test No.41

| Size | Size Distribution (%) | | | | EA | EC |
|---|---|---|---|---|---|---|
| Micr. | O/F | SAND | CAL.F | Mea.F | % | % |
| 2803 | 0.00 | 0.04 | 0.02 | 0.06 | 100.00 | 100.00 |
| 992 | 0.51 | 43.43 | 27.15 | 27.19 | 99.29 | 98.82 |
| 350 | 1.89 | 10.00 | 6.92 | 7.10 | 89.64 | 82.88 |
| 248 | 3.35 | 5.05 | 4.41 | 4.38 | 71.15 | 52.32 |
| 174 | 4.46 | 3.81 | 4.06 | 4.05 | 58.29 | 31.06 |
| 104 | 11.95 | 6.41 | 8.51 | 8.55 | 46,74 | 11.97 |
| 63 | 6.70 | 2.87 | 4.32 | 4.24 | 41.21 | 2.82 |
| -63 | 71.14 | 28.39 | 44.61 | 44.43 | 39.50 | 0.00 |

RF=40.5670408 OFW=3.08 SW=5.05

Table AI.42 Results of Test No.42

| Size | Size Distribution (%) | | | | EA | EC |
|---|---|---|---|---|---|---|
| Micr. | O/F | SAND | CAL.F | Mea.F | % | % |
| 2803 | 0.00 | 0.01 | 0.01 | 0.07 | 100.00 | 100.00 |
| 992 | 1.96 | 60.11 | 7.47 | 6.57 | 76.23 | 75.84 |
| 350 | 3.46 | 13.94 | 4.45 | 4.13 | 29.65 | 28.49 |
| 248 | 4.00 | 6.39 | 4.23 | 4.28 | 14.32 | 12.90 |
| 174 | 4.74 | 3.65 | 4.64 | 4.58 | 7.45 | 5.93 |
| 104 | 12.26 | 4.00 | 11.48 | 11.62 | 3.30 | 1.71 |
| 63 | 6.37 | 1.22 | 5.88 | 5.88 | 1.96 | 0.35 |
| -63 | 67.21 | 10.59 | 61.85 | 62.87 | 1.62 | 0.00 |

RF=2.04165525 OFW=9.53 SW=1.00

Table AI.43 Results of Test No.43

| Size | | Size Distribution (%) | | | EA | EC |
|---|---|---|---|---|---|---|
| Micr. | O/F | SAND | CAL.F | Mea.F | % | % |
| 2803 | 0.00 | 0.40 | 0.05 | 0.00 | 100.00 | 100.00 |
| 992 | 13.73 | 67.06 | 20.92 | 11.98 | 43.20 | 41.24 |
| 350 | 8.87 | 10.10 | 9.04 | 7.83 | 15.06 | 12.13 |
| 248 | 6.37 | 3.64 | 6.00 | 6.45 | 8.17 | 5.00 |
| 174 | 6.27 | 2.58 | 5.77 | 6.45 | 6.02 | 2.78 |
| 104 | 13.37 | 4.21 | 12.14 | 13.77 | 4.67 | 1.38 |
| 63 | 6.12 | 1.53 | 5.50 | 5.82 | 3.75 | 0.42 |
| -63 | 47.27 | 10.48 | 42.31 | 47.70 | 3.34 | 0.00 |

RF=4.09795526 OFW=16.97 SW=2.64

Table AI.44 Results of Test No.44

| Size | Size Distribution (%) | | | | EA | EC |
|---|---|---|---|---|---|---|
| Micr. | O/F | SAND | CAL.F | Mea.F | % | % |
| 2803 | 0.00 | 0.04 | 0.03 | 0.04 | 100.00 | 100.00 |
| 992 | 6.59 | 19.23 | 15.15 | 16.06 | 85.95 | 62.37 |
| 350 | 5.79 | 6.25 | 6.10 | 6.06 | 69.36 | 17.92 |
| 248 | 5.52 | 5.63 | 5.59 | 5.65 | 68.14 | 14.66 |
| 174 | 5.43 | 5.45 | 5.44 | 5.52 | 67.79 | 13.72 |
| 104 | 11.66 | 10.98 | 11.20 | 11.02 | 66.38 | 9.95 |
| 63 | 6.45 | 5.54 | 5.83 | 5.36 | 64.30 | 4.37 |
| -63 | 58.56 | 46.88 | 50.65 | 50.29 | 62.67 | 0.00 |

RF=63.6101084 OFW=3.34 SW=7.01

Table AI.45 Results of Test No.45

| Size | Size Distribution (%) | | | | EA | EC |
|---|---|---|---|---|---|---|
| Micr. | O/F | SAND | CAL.F | Mea.F | % | % |
| 2803 | 0.00 | 0.15 | 0.03 | 0.04 | 100.00 | 100.00 |
| 992 | 10.29 | 38.64 | 15.11 | 15.04 | 43.46 | 36.58 |
| 350 | 6.44 | 8.62 | 6.81 | 6.75 | 21.50 | 11.95 |
| 248 | 6.33 | 5.21 | 6.14 | 6.10 | 14.42 | 4.00 |
| 174 | 6.33 | 4.60 | 6.04 | 6.15 | 12.95 | 2.35 |
| 104 | 13.39 | 8.74 | 12.60 | 12.83 | 11.78 | 1.05 |
| 63 | 6.16 | 3.68 | 5.74 | 5.76 | 10.89 | 0.05 |
| -63 | 51.06 | 30.36 | 47.54 | 47.33 | 10.85 | 0.00 |

RF=11.9949381 OFW=12.04 Sw=2.47

Table AI.46 Results of Test No.46

| Size | | Size Distribution (%) | | | EA | EC |
|---|---|---|---|---|---|---|
| Micr. | O/F | SAND | CAL.F | Mea.F | % | % |
| 2803 | 0.00 | 0.20 | 0.02 | 0.01 | 100.00 | 100.00 |
| 992 | 10.62 | 42.46 | 14.29 | 14.62 | 34.22 | 29.51 |
| 350 | 6.73 | 8.44 | 6.93 | 6.73 | 14.03 | 7.87 |
| 248 | 5.63 | 4.98 | 5.56 | 5.63 | 10.32 | 3.90 |
| 174 | 5.87 | 4.13 | 5.67 | 5.87 | 8.39 | 1.83 |
| 104 | 12.88 | 7.59 | 12.27 | 12.88 | 7.12 | 0.47 |
| 63 | 5.72 | 3.29 | 5.44 | 5.02 | 6.96 | 0.30 |
| -63 | 52.55 | 28.91 | 49.83 | 49.24 | 6.68 | 0.00 |

RF=7.64408988 OFW=12.29 SW=1.60

# APPENDIX II

## SIMULATION PROGRAGGM

```
100  REM
110  REM  *** PROGRAM NAME: SIMULATION PROGRAM ***
120  REM
130  REM  ******************************
140  REM  PROGRAM TO SIMULATE A GRINDING
150  REM  CIRCUIT WHICH CONSISTS OF A
160  REM  BALL MILL AND A SPIRAL CLASSI-
170  REM  FIER
180  REM  ******************************
190  REM
200  REM  ******************************
210  REM  SPECIFICATION OF VARIABLES AND
220  REM      PARAMETERS
230  REM  ******************************
240  REM  SW(L)=MASS FLOW RATE(TPH) IN
250  REM  STREAM L
260  REM  P(L)=PULP DENSITY (%) IN
270  REM  STREAM L
280  REM  W1=WATER ADDITION TO BALL
290  REM  MILL (TPH)
300  REM  W2=WATER ADDITION TO SPI-
310  REM  RAL CLASSIFIER (TPH)
320  REM  VW(L)=VOLUME FLOW RATE OF
330  REM  WATER IN STREAM L
340  REM  TI=BALL MILL MEAN RESIDENCE
350  REM  TIME,MIN.
360  REM  RE=THE CALCULATED CIRCULATING
370  REM  LOAD,PCT
380  REM  F1(I,L)=THE MASS FRACTION OF
390  REM  THE ITH SIEVE SIZE IN STREAM L
400  REM  BK=BREAKAGE RATE OF THE ITH
410  REM     SIZE FRACTION
420  REM  X9(I)=SIEVE SIZE (MICRONS)
430  REM  M9(I,L)=WEIGHT% RETAINED IN
440  REM  SIZE FRACTION I AND STREAM L
450  REM  HU=BALL MILL HOLD UP
460  REM  EA(I)=ACTUAL EFFICIENCY,PCT
470  REM  EC(I)=CORRECTED EFFICIENCY,PCT
480  REM  VT(L)=THE TOTAL VOLUME IN
490  REM  STREAM L
500  REM  DT=TIME INTERVAL
510  REM  X1=VOLUME FLOW RATE TO THE
520  REM     CLASSIFIER,L/MIN.
530  REM  X2=PULP DENSITY IN THE FEED
540  REM     OF CLASSIFIER,PCT
550  REM  X3=% WT. LARGER THAN 425 MICRONS
```

```
560  REM     IN TE FEED OF THE CLASSIFIER
570  REM  X4=% WT. LESS THAN 53 MICRONS
580  INT HEFEEDOFTHECLASS IF IER
590  REM  X5=WEIR HEIGHT OF SIRAL CLA-
600  REM     SSIFIER,MM
610  REM  X6=SLOPE OF THE SPIRAL CLASSIFIER,DEGREES
620  REM  SG=SPECIFIC GRAVITY OF ORE
630  REM  M=THE NUMBER OF SIZE FRACTION
640  REM  L=THE NUMBER OF STREAMS
650  REM  K1=CONSTANT
660  REM  K2=CONSTANT
670  REM  K3=CONSTANT
680  REM  K4=CONSTANT
690  REM  FZ=% WT. OF THE FINEST SIZE
700  REM     FRACTION IN THE SAND
710  REM  WW(L)=WEIGHT OF WATER IN
720  REM  STREAM L
730  REM  PW(L)=WEIGHT OF SLURRY IN
740  REM  STREAM L
750  REM  GM(I)=GEOMETRIC MEAN OF THE
760  REM      ITH SIZE FRACTION
770  REM
780  REM
790  REM
1000  PRINT  CHR$ (4)"BLOAD CCSNEW,A$C100"
1010  GOTO 2460
1020  REM  **** SUB  INPUT ****
1030  REM
1040  PRINT "INPUT INITIAL DATA"
1050  PRINT "BALL MILL DIM.,D,L(METER)"
1060  INPUT D,L
1070  PRINT "MILL OPERATION CONDITIONS"
1080  PRINT "MASS FLOW RATE ;IN FRESH FEED,SW(1),TPH"
1090  INPUT SW(1)
1100  PRINT "CHARGE FILLING,CF(%)              "
1110  INPUT CF
1120  PRINT "ORE SPECIFIC GRAVITY,SG"
1130  INPUT SG
1140  PRINT "POROSITY OF THE CHARGE,PC"
1150  INPUT PC
1160  PRINT "% SOLIDS BY VOLUME,SV"
1170  INPUT SV
1180  REM  CALCULATE HOLD UP,HU
1190 HU = D * D * (3.14 / 4) * L * CF * PC * SV * SG
1200  REM  NO. OF SIZE FRACTION,M
1210 M = 8
1220 IM = M - 1
```

```
1230  FOR I = 0 TO M
1240  READ X9(I),M9(I,1),BK(I)
1250  NEXT I
1260  DATA  598,20.06,.5
1270  DATA  425,3.56,0.4897
1280  DATA  300,3.98,.4614
1290  DATA  212,5.33,0.3412
1300  DATA  148,5.49,0.2082
1310  DATA  106,7,0.1233
1320  DATA  75,7.96,0.0788
1330  DATA  53,6.91,0.0506
1340  DATA  -53,39.71,0
1350 P(1) = 85
1360  PRINT "WEIR HEIGHT OF CLASSIFIER,X5(MM)"
1370  INPUT X5
1380  PRINT "SLOPE OF CLASSIFIER,X6(DEGREE)"
1390  INPUT X6
1400 K1 =  - 1.515645:K2 =  - 0.363643
1410 K3 = 4.7073883:K4 =  - 19.342319
1420  PRINT "EXTRA WATER TO THE MILL,W1(T/H)"
1430  INPUT W1
1440  PRINT "EXTRA WATER TO THE CLASSIFIER,W2(T/H)"
1450  INPUT W2
1460  RETURN
1470  REM
1480  REM  **** SUB SPIRAL CLASSIFIER ****
1490  REM
1500 MM = 2
1510 C = K3 + .336131E - 2 * X1 ^ 2 - .3504735E - 2 * X3 ^ 2
1520 C = C - .1167761E - 2 * X1 * X5 + .1485681E - 1 * X3 *
X6
1530 C = C - .3885253E - 2 * X5 * X6 + .1154215E - 5 * X5 ^
3
1540 RF =  EXP (C)
1550  PRINT : PRINT "RF = ";RF;" PCT": PRINT
1560 RF = RF / 100
1570 WW(3) = RF * WW(2)
1580 WW(4) = WW(2) - WW(3)
1590 WW(3) = WW(3) + W2
1600 A = (K2 + 0.163837 * X2 + 0.3611753E - 02 * X3 * X3)
1610 B = 0.962175E - 04 * X4 * X4 + 0.9948503E - 03 * X1 *
X2
1620 W =  - 0.4137373E - 02 * X2 * X3
1630 D50C =  EXP (A + B + W)
1640  PRINT "D50C = ";D50C;" MICRONS"
1650 T = 1.742944 * X1 + 1.227213 * X4 + 0.0376816 * X1 * X3
+ K4
```

```
1660 U =  - 0.01831538 * X1 * X5 + 0.015492 * X2 * X4
1670 V = 0.06874171 * X3 * X6 - 0.1269083 * X4 * X6
1680 X = 0.9441318E - 05 * X5 * X5 * X5 - 0.0106245 * X3 *
X5
1690 FZ = T + U + V + X
1700  IF FZ < 0.01 THEN FZ = 0.01
1710  PRINT "FZ = ";FZ;" PCT"
1720 FZ = FZ / 100
1730  FOR I = 1 TO IM
1740 GM(I) = (X9(I - 1) * X9(I)) ^ 0.5
1750  NEXT I
1760 GM(0) = X9(0)
1770 GM(M) = X9(M)
1780  FOR I = 0 TO IM
1790 EC(I) = 1 -  EXP ( - 0.693 * (GM(I) / D50C) ^ MM)
1800 EA(I) = EC(I) * (1 - FZ) + FZ
1810  PRINT "EA(";I;") = ";EA(I);"   EC(";I;") = ";EC(I)
1820  NEXT I
1830 EA(M) = FZ
1840 EC(M) = 0
1850  PRINT "EA(M) = ";EA(M);"   EC(M) = ";EC(M)
1860 SW(3) = 0:SW(4) = 0
1870  FOR I = 0 TO M
1880 F1(I,3) = EA(I) * F1(I,2)
1890 F1(I,4) = F1(I,2) - F1(I,3)
1900 SW(3) = SW(3) + F1(I,3)
1910 SW(4) = SW(4) + F1(I,4)
1920  NEXT I
1930  PRINT "SW(4)=";SW(4)
1940 PW(3) = SW(3) + WW(3)
1950 PW(4) = SW(4) + WW(4)
1960 P(3) = 100 * SW(3) / PW(3)
1970 P(4) = 100 * SW(4) / PW(4)
1980  FOR I = 0 TO M
1990 M9(I,3) = 100 * F1(I,3) / SW(3)
2000 M9(I,4) = 100 * F1(I,4) / SW(4)
2010  NEXT I
2020  RETURN
2030  REM
2040  REM  *** BALL MILL MODEL SUBROUTINE
2050  REM  *** THE MODEL USES THE CUMULATIVE-BASED
2060  REM  *** RATE OF BREAKAGE (REF.HORST & BASSAERAR)
2070  REM
2080 SUM = 0
2090  FOR I = 0 TO IM
2100 F1(I,3) = SUM + F1(I,3)
2110 SUM = F1(I,3)
```

```
2120  NEXT I
2130  REM
2140  REM  *** F1(I,3) & F1(I,5) ARE CUMULATIVE MTPH COARSER
2150  FOR I = 0 TO IM
2160 F1(I,5) = F1(I,3) *  EXP ( - BK(I) * TI)
2170  PRINT "F1(";I;",5) = ";F1(I,5);" MTPH"
2180  NEXT I
2190 F1(M,5) = SW(3)
2200  PRINT "F1(";M;",5) = ";F1(M,5);" MTPH - CUMULATIVE"
2210  REM
2220  REM  *** FINDING THE MTPH IN NON-CUMULATIVE FORM
2230  PRINT
2240  FOR I = 1 TO M
2250 L = I - 1
2260 F(I) = F1(I,5) - F1(L,5)
2270  NEXT I
2280  REM
2290  REM  *** PRINTING THE RESULTS
2300  PRINT
2310 F(0) = F1(0,5)
2320  REM
2330  REM  *** FINDING THE WT PCT RETAINED
2340 SW(5) = SW(3):WW(5) = WW(3)
2350  FOR I = 0 TO M
2360 M9(I,5) = 100 * F(I) / SW(5)
2370  NEXT I
2380  PRINT
2390  FOR I = 0 TO M
2400  PRINT "M9(";I;",5) = ";M9(I,5);" PCT"
2410  NEXT I
2420  FOR I = 0 TO M
2430 F1(I,5) = F(I)
2440  NEXT I
2450  RETURN
2460  REM   **** MAIN PROGRAM ****
2470  REM
2480  DIM F1(10,5),M9(10,5)
2490 KO = 1
2500  REM  GO SUB INPUT
2510  GOSUB 1020
2520  FOR I = 0 TO M
2530 F1(I,1) = M9(I,1) * SW(1) / 100
2540 F1(I,5) = 0
2550  NEXT I
2560 SW(5) = 0
2570 VW(5) = 0
2580 WW(5) = 0
```

```
2590 PW(5) = 0
2600  REM
2610  REM  CALCULATE FRACTION MASS FLOWRATE, MTPH
2620  FOR I = 0 TO M
2630 F1(I,1) = (M9(I,1) * SW(1)) / 100
2640 F1(I,2) = F1(I,1) + F1(I,5)
2650  NEXT I
2660 WW(1) = SW(1) / (P(1) / 100) - SW(1)
2670 PW(1) = SW(1) + WW(1)
2680 VW(1) = WW(1)
2690 VT(1) = SW(1) / SG + VW(1)
2700 WW(2) = WW(1) + WW(5) + W1
2710 SW(2) = SW(1) + SW(5)
2720 PW(2) = SW(2) + WW(2)
2730 P(2) = (SW(2) / PW(2)) * 100
2740 VW(2) = WW(2)
2750 VT(2) = SW(2) / SG + VW(2)
2760  FOR I = 0 TO M
2770 M9(I,2) = 100 * F1(I,2) / SW(2)
2780  NEXT I
2790  REM
2800 X1 = 1000 * VT(2) / 60
2810 X2 = P(2)
2820 X3 = M9(0,2) + M9(1,2)
2830 X4 = M9(M,2)
2840  GOSUB 1470
2850 TI = 60 * HU / PW(3)
2860  REM  GO SUB BALL MILL
2870  REM
2880  GOSUB 2040
2890 PW(5) = PW(3)
2900 P(5) = P(3)
2910 VW(5) = VW(3)
2920 VT(5) = VT(3)
2930  REM
2940  REM
2950  REM
2960 RE = 100 * SW(5) / SW(1)
2970  IF KO > 30 THEN 3040
2980 AC =  ABS ((SW(1) - SW(4)) * 100 / SW(1))
2990  IF AC <  = .1 GOTO 3070
3000  PRINT : PRINT "AC = ";AC;" PCT"
3010 KO = KO + 1
3020  PRINT "KO=";KO
3030  GOTO 2620
3040  PRINT "OVER 30 ITERATION"
3050  GOTO 3150
```

```
3060  GOTO 3090
3070  PRINT "CONVERGENCE ACHIEVED"
3080  GOTO 3150
3090  PRINT "DO YOU WANT TO CHANGE VARIABLES?"
3100  PRINT "IF YES,X=1;IF NOT,X=0"
3110  INPUT X
3120  IF X = 0 THEN 3140
3130  GOTO 2460
3140  END
3150  REM
3160  REM  **** SUB  OUTPUT ****
3170  REM
3180 D$ =  CHR$ (4):DM$ = "PR#0":DP$ = "PR#1"
3190  PRINT D$;DP$
3200  PRINT  TAB( 23);"PRINTOUT OF SIMULATION RESULTS"
3210  PRINT  TAB( 23);"********************************"
3220  PRINT : PRINT
3230 A1$ = "                    MEAN RESIDENCE TIME = ##.##
MIN"
3240  &  PRINT USEA1$;TI
3250  PRINT
3260 A$ = "                    CIRCULATING LOAD = ###.## PCT"
3270  &  PRINT USEA$;RE
3280  PRINT : PRINT
3290 B$ = "                 ####         ##.##"
3300  PRINT  TAB( 17);"WEIGHT PERCENT RETAINED OF STREAMS
INDICATED"
3310  PRINT  TAB(
17);"----------------------------------------------"
3320  PRINT
3330  FOR L = 1 TO 3
3340  PRINT
3350  PRINT  TAB( 24);"STREAM NO. ";L
3360  PRINT  TAB( 24);"-----------"
3370  PRINT
3380  PRINT  TAB( 17);"SIZE   PCT RETAINED"
3390  FOR I = 0 TO M
3400  &  PRINT USEB$;X9(I),M9(I,L)
3410  NEXT I
3420  NEXT L
3430  PRINT D$;DM$
3440  HOME
3450  VTAB (10)
3460  PRINT "ENTER A FRESH PAGE FOR CONTINUING PRINTOUT"
3470  PRINT : PRINT "PRESS ANY NUMBER TO CONTINUE,XX"
3480  INPUT XX
3490  PRINT D$;DP$
```

```
3500  FOR L = 4 TO 5
3510  PRINT
3520  PRINT  TAB( 24);"STREAM NO. ";L
3530  PRINT  TAB( 24);"-----------"
3540  PRINT
3550  PRINT  TAB( 17);"SIZE    PCT RETAINED"
3560  FOR I = 0 TO M
3570  &  PRINT USEB$;X9(I),M9(I,L)
3580  NEXT I
3590  NEXT L
3600  PRINT : PRINT
3610  PRINT  TAB( 20);"WEIGHT PCT SOLIDS"
3620  PRINT  TAB( 20);"-----------------"
3630  PRINT  TAB( 17);"STREAM 1 =";P(1)
3640  PRINT  TAB( 17);"STREAM 2 =";P(2)
3650  PRINT  TAB( 17);"STREAM 2 =";P(3)
3660  PRINT  TAB( 17);"STREAM 4 =";P(4)
3670  PRINT  TAB( 17);"STREAM 5 =";P(5)
3680  PRINT D$;DM$
3690  HOME
3700  VTAB (10)
3710  VTAB (10)
3720  PRINT
3730  PRINT  TAB( 17);"ENTER A FRESH PAGE FOR DATA PRINTOUT"
3740  PRINT "PRESS ANY NUMBER TO CONTINUE,XX"
3750  INPUT XX
3760  PRINT D$;DP$
3770  PRINT : PRINT
3780  PRINT  TAB( 17);"INPUT DATA FOR THIS SIMULATION WERE"
3790  PRINT  TAB( 17);"***********************************"
3800  PRINT : PRINT
3810  PRINT  TAB( 12);"CUMULATIVE-BASIS BREAKAGE RATE"
3820  PRINT  TAB( 12);"------------------------------"
3830  PRINT
3840  PRINT
3850  PRINT  TAB( 13);"SIZE    BREAK.RATE": PRINT
3860 C$ = "                 ####    #.###"
3870  FOR I = 0 TO M
3880  &  PRINT USEC$;X9(I),BK(I)
3890  NEXT I
3900  PRINT : PRINT
3910  PRINT D$;DM$
3920  HOME
3930  VTAB (12)
3940  PRINT  TAB( 12);"ENTER A FRESH PAGE AND CONTINUE
PRINTOUT"
3950  PRINT : PRINT
```

```
3960  PRINT  TAB( 12);"PRESS ANY NUMBER TO CONTINUE,XX"
3970  INPUT XX
3980  PRINT D$;DP$
3990  PRINT  TAB( 17);"INPUT DATA FOR THIS
SIMULATION(CONTIUED)"
4000  PRINT  TAB(
17)"--------------------------------------------"
4010  PRINT : PRINT
4020  PRINT  TAB( 17);"BALL MILL HOLD-UP = ";HU;" METRIC
TONNES": PRINT
4030  PRINT  TAB( 17);"FRESH FEED TONNAGE = ";SW(1);" MTPH":
PRINT
4040  PRINT  TAB( 17);"WATER FLOW RATE ADDED IN THE
CLASSIFIER,TPH=";W2
4050  PRINT
4060  PRINT  TAB( 17);"WATER SPLIT FACTOR, RF = ";100 * RF;"
PCT": PRINT
4070  PRINT  TAB( 17);"ORE SPECIFIC GRAVITY = ";SG;" G/CC"
4080  PRINT
4090  PRINT  TAB( 17);"SPIRAL CLASSIFIER SELECTIVITY
INDICES,PCT"
4100  PRINT  TAB(
17);"-------------------------------------------"
4110 F$ = "                ####    ###.##"
4120  PRINT  TAB( 17);"SIZE    EC(I)"
4130  PRINT
4140  FOR I = 0 TO IM
4150  &  PRINT USEF$;GM(I),100 * EC(I)
4160  NEXT I
4170  END
```

# APPENDIX III

## METHODS TO DETERMINE d50c

Table AIII.1 Comparision of d50c Values Coming From Different Calculated Methods

| Test No. | d50c (microns) L | S | M | D |
|---|---|---|---|---|
| 1 | 126.3 | 128.6 | 151.8 | 125.9 |
| 2 | 115.2 | 157.8 | 199.6 | 158.5 |
| 3 | 169.0 | 169.0 | 188.8 | 177.8 |
| 4 | 103.2 | 102.9 | 128.9 | 100.5 |
| 5 | 144.9 | 146.0 | 165.1 | 141.3 |
| 6 | 176.7 | 175.0 | 199.3 | 173.8 |
| 7 | 292.1 | 277.9 | 339.0 | 251.2 |
| 8 | 255.7 | 240.7 | 263.1 | 251.5 |
| 9 | 321.3 | 300.1 | 345.2 | 260.3 |
| 10 | 344.6 | 340.8 | 302.5 | 316.2 |
| 11 | 322.1 | 290.2 | 279.9 | 251.3 |
| 12 | 456.4 | 511.8 | 432.5 | 446.7 |
| 13 | 412.8 | 452.5 | 357.7 | 398.1 |
| 14 | 1003.9 | 1008.9 | 1181.2 | 1000.2 |
| 15 | 1009.0 | 1134.5 | 1260.8 | 1122.1 |
| 16 | 376.4 | 393.3 | 429.9 | 380.2 |
| 17 | 416.6 | 456.1 | 374.6 | 446.7 |
| 18 | 631.8 | 683.4 | 451.5 | 582.1 |
| 19 | 397.1 | 428.9 | 390.3 | 398.1 |
| 20 | 600.5 | 666.7 | 532.6 | 574.4 |
| 21 | 804.3 | 822.8 | 780.4 | 758.5 |
| 22 | 844.4 | 792.4 | 835.4 | 760.2 |
| 23 | 406.9 | 443.6 | 351.5 | 398.1 |
| 24 | 380.1 | 402.1 | 393.2 | 389.0 |
| 25 | 731.3 | 772.0 | 749.9 | 707.9 |
| 26 | 793.7 | 799.0 | 690.5 | 741.3 |
| 27 | 1917.5 | 1673.0 | 1848.7 | 1584.9 |
| 28 | 1794.4 | 1600.3 | 1719.9 | 1585.1 |
| 29 | 2410.2 | 1754.2 | 1988.6 | 1584.8 |
| 30 | 1448.6 | 1463.7 | 1203.9 | 1412.5 |
| 31 | 205.4 | 204.9 | 207.9 | 199.5 |
| 32 | 226.2 | 224.7 | 268.4 | 223.9 |
| 33 | 267.8 | 267.6 | 315.7 | 251.2 |
| 34 | 216.5 | 218.3 | 258.1 | 199.5 |
| 35 | 319.9 | 319.1 | 335.2 | 316.2 |
| 36 | 2520.7 | 1750.6 | 2741.5 | 1584.9 |
| 37 | 2638.6 | 1689.6 | 1766.2 | 1620.3 |
| 38 | 1935.5 | 1592.8 | 1815.7 | 1623.1 |
| 39 | 275.0 | 317.6 | 383.9 | 316.2 |
| 40 | 894.2 | 897.8 | 621.6 | 794.3 |
| 41 | 240.1 | 239.9 | 268.8 | 234.4 |
| 42 | 597.6 | 641.6 | 512.5 | 562.3 |
| 43 | 1218.3 | 1262.0 | 1062.5 | 1174.9 |
| 44 | 953.5 | 813.3 | 873.0 | 758.6 |
| 45 | 1356.2 | 1375.2 | 691.7 | 1333.5 |
| 46 | 1562.6 | 1518.4 | 1295.6 | 1549.1 |

Note: L: Lagrange method; S: Straight line method
M: From slope m; D: Directly from curve

```
10   REM
20   REM   *** PROGRAM NAME: AIII.2 ***
30   REM
40   REM   *** PROGRAM TO CALCULATE D50C BASED ***
50   REM   *** ON EXPERIMENTAL DATA USING      ***
60   REM   *** LAGRANGE INTERPOLATION METHOD   ***
70   REM
80   DIM D0(50),D1(50),D(50),D2(50),E1(50)
90   DIM E2(50),E0(50),A1(50),A2(50),A3(50)
100   DIM B1(50),B2(50),B3(50),C1(50),C2(50)
110   DIM C3(50)
120   READ N
130   DATA  46
140   REM
150   REM   *** INPUT DATA ***
160   FOR I = 1 TO N
170   READ D2(I),E2(I),D1(I),E1(I),D0(I),E0(I)
180   NEXT I
190   DATA  174,69.79,104,39.27,13,15.01
200   DATA  248,68.86,174,59.97,104,16.88
210   DATA  248,70.34,174,51.28,104,33.30
220   DATA  174,67.76,104,50.28,63,27.73
230   DATA  248,66.53,174,54.95,104,42.57
240   DATA  248,73.02,174,49.67,104,42.45
250   DATA  350,66.53,248,43.16,174,34.38
260   DATA  248,52.57,174,26.51,104,20.09
270   DATA  350,64.65,248,34.68,174,24.40
280   DATA  350,51.04,248,39.53,174,34.47
290   DATA  350, 60.31,248,42.73,174,37.91
300   DATA  992,84.73,350,38.30,248,13.62
310   DATA  992,82.11,350,43.92,248,19.22
320   DATA  2803,100,992,49.53,350,13.05
330   DATA  2803,100,992,45.73,350,11.28
340   DATA  992,94.55,350,46.73,248,27.89
350   DATA  992,92.85,350,41.52,248,18.65
360   DATA  992,72.91,350,25.25,248,12.44
370   DATA  992,89.38,350,44.48,248,18.23
380   DATA  992,74.01,350,26.62,248,9.40
390   DATA  992,63.04,350,13.57,248,4.02
400   DATA  992,67.53,350,11.15,248,4.83
410   DATA  992,87.83,350,43.54,248,15.98
420   DATA  992,87.73,350,46.67,248,22.73
430   DATA  992,67.91,350,15.65,248,2.88
440   DATA  992,66.48,350,11.66,248,2.53
450   DATA  2803,100,992,19.87,350,3.12
460   DATA  2803,100,992,24.71,350,7.90
470   DATA  2803,100,992,13.66,350,2.25
```

```
480  DATA  2803,100,992,32.39,350,6.9
490  DATA  248,66.38,174,38.27,104,13.15
500  DATA  248,58.52,174,31.50,104,9.77
510  DATA  350,76.05,248,43.82,174,21.08
520  DATA  350,85.62,248,59.28,174,36.19
530  DATA  992,80.68,350,63.40,248,19.13
540  DATA  2803,100,992,13.96,350,3.66
550  DATA  2803,100,992,18.67,350,10.29
560  DATA  2803,100,992,25.18,350,11.95
570  DATA  992,94.98,350,59.41,248,29.82
580  DATA  992,56.26,350,13.59,248,6.43
590  DATA  350,82.88,248,52.32,174,31.06
600  DATA  992,75.84,350,28.49,248,12.90
610  DATA  2803,100,992,41.24,350,12.13
620  DATA  992,62.37,350,17.92,248,14.66
630  DATA  2803,100,992,36.58,350,11.95
640  DATA  2803,100,992,29.51,350,7.87
650  REM
670  PRINT "D2(1)=";D2(1)
680  PRINT "E2(1)=";E2(1)
690  PRINT "D1(1)=";D1(1)
700  PRINT "E1(1)=";E1(1)
710  PRINT "D0(1)=";D0(1)
720  PRINT "E0(1)=";E0(1)
730  REM
740  REM  *** CALCULATE D50C ***
750  REM
760 E = 50
770  FOR I = 1 TO N
780 A1(I) = (E - E1(I)) * (E - E2(I)) * D0(I)
790 A2(I) = (E - E0(I)) * (E - E2(I)) * D1(I)
800 A3(I) = (E - E0(I)) * (E - E1(I)) * D2(I)
810 B1(I) = (E0(I) - E1(I)) / (E0(I) - E2(I))
820 B2(I) = (E1(I) - E0(I)) / (E1(I) - E2(I))
830 B3(I) = (E2(I) - E0(I)) / (E2(I) - E1(I))
840 C1(I) = A1(I) / B1(I)
850 C2(I) = A2(I) / B2(I)
860 C3(I) = A3(I) / B3(I)
870 D(I) = C1(I) + C2(I) + C3(I)
880  NEXT I
890  REM
900  REM  *** OUTPUT RESULTS ***
910  PRINT  CHR$ (4);"PR#3"
920  PRINT : PRINT : PRINT
930  FOR I = 1 TO 60
940  PRINT "X";
950  NEXT I
960  PRINT
```

```
970  PRINT : PRINT
980  PRINT  TAB( 20);"THE VALUES OF D50C"
990  PRINT  TAB( 20);"******************"
1000  PRINT
1010 E$ = "TEST NO.          D50C"
1020 B$ = "  ##            ####.#"
1030  PRINT E$
1040  PRINT
1050  FOR I = 1 TO N
1060  &  PRINT USEB$;I,D(I)
1070  NEXT I
1080  PRINT : PRINT
1090  PRINT  CHR$ (12)
1100  PRINT
1110  PRINT "C1(1)=";C1(1)
1120  PRINT "C2(1)=";C2(1)
1130  PRINT "C3(1)=";C3(1)
1140  PRINT
1150  CHR$ (4);"PR#0)"
1160  END
```

```
100  REM
110  REM  *** PROGRAM NAME: AIII.3        ***
120  REM
130  REM
140  REM  *** PROGRAM TO CALCULATE D50C  ***
150  REM  *** BASED ON EXPERIMENTAL DATA ***
160  REM  *** USING LINEAR INTERPOLATION ***
170  REM  *** METHOD                     ***
180  REM
190  REM
200  REM  DIM D0(50),D1(50),D2(50),E1(50)
210  REM  DIM E2(50),A(50),B(50)
220  READ N
230  DATA  52
240  REM
250  REM  ****INPUT DATA ****
260  REM
270  FOR I = 1 TO N
280  READ D2(I),D1(I),E2(I),E1(I)
290  NEXT I
300  DATA      174,104,69.79,39.27
310  DATA     174,104,59.97,16.88
320  DATA     174,104,51.28,33.30
330  DATA     174,104,67.76,50.28
340  DATA      174,104,54.95,42.57
350  DATA     248,174,73.02,49.67
360  DATA      350,248,66.53,43.16
370  DATA   248,174,52.57,26.51
380  DATA      350,248,64.65,34.68
390  DATA      350,248,51.04,39.53
400  DATA      350,248,60.31,42.73
410  DATA      992,350,84.73,38.30
420  DATA    992,350,82.11,43.90
430  DATA      2803,992,100,49.53
440  DATA      2803,992,100,45.73
450  DATA      992,350,94.55,46.73
460  DATA      992,350,92.85,41.52
470  DATA      992,350,72.91,25.25
480  DATA      992,350,89.38,44.48
490  DATA  992,350,74.01,26.62
500  DATA      992,350,63.04,13.57
510  DATA      992,350,67.53,11.15
520  DATA  992,350,87.83,43.54
530  DATA      992,350,87.73,46.67
540  DATA  992,350,67.91,15.65
550  DATA      992,350,66.48,11.66
560  DATA      2803,992,100,19.87
```

```
570  DATA      2803,992,100,24.71
580  DATA      2803,992,100,13.66
590  DATA      2803,992,100,32.39
600  DATA      248,174,66.38,38.27
610  DATA      248,174,58.52,31.50
620  DATA      350,248,76.05,43.82
630  DATA      248,174,59.28,36.19
640  DATA      350,248,63.40,19.13
650  DATA      2803,992,100,13.96
660  DATA  2803,992,100,18.67
670  DATA      2803,992,100,25.18
680  DATA    350,248,59.41,29.82
690  DATA      992,350,56.26,13.59
700  DATA      248,174,52.32,31.06
710  DATA      992,350,75.84,28.49
720  DATA      2803,992,100,41.24
730  DATA      992,350,62.37,17.92
740  DATA      2803,992,100,36.58
750  DATA    2803,992,100,29.51
760  REM
770  REM  ****CALCULATE D50(C) ****
780  REM
790  REM  EQUATION FOR CACULATING D50(C) IS :
800  REM  (E0-E1)/(D0-D1)=(E2-E1)/(D2-D1)
810 E0 = 50
820  FOR I = 1 TO N
830 A(I) = (E0 - E1(I)) * (D2(I) - D1(I))
840 B(I) = (E2(I) - E1(I))
850 D0(I) = D1(I) + A(I) / B(I)
860  NEXT I
870  REM
880  REM  ****OUTPUT RESULTS ****
890  PRINT  CHR$ (4);"PR#1"
900  PRINT : PRINT : PRINT
910  FOR I = 1 TO 60
920  PRINT "X";
930  NEXT I
940  PRINT : PRINT : PRINT
950  PRINT  TAB( 20);"THE VALUE OF D50(C)"
960  PRINT  TAB( 20);"*******************"
970  PRINT
980 E$ = "TEST NO.                    D50(C)"
990 B$ = " ##                          ####.#"
1000  PRINT E$
1010  PRINT
1020  FOR I = 1 TO N
1030  &  PRINT USEB$;I,D0(I)
1040  NEXT I
```

```
1050  PRINT : PRINT
1060  PRINT  CHR$ (12)
1070  PRINT
1080  PRINT
1090  PRINT  CHR$ (4);"PR#0"
1100  PRINT "D2(1)=";D2(1)
1110  PRINT "D1(1)=";D1(1)
1120  PRINT "E2(1)=";E2(1)
1130  PRINT "E1(1)=";E1(1)
1140  END
```

```
10  REM
20  REM  *** PROGRAM NAME: AIII.4        ***
22  REM
24  REM  *** PROGRAM TO CALCULATE D50C   ***
26  REM  *** AND THE SLOPE OF THE REDUCED-***
28  REM  *** PERFORMANCE CURVE, M, USING  ***
30  REM  *** ROSIN-RAMMLER EQUATION       ***
100  DIM X(15),Y(15)
105  PRINT "ENTER NO. OF DATA POINTS": PRINT
106  INPUT N: PRINT
110  HOME
120  PRINT "ENTER X(I), Y(I) DATA POINTS": PRINT
130  PRINT "X(I)=SIZE; Y(I)=YC(I), PCT"
140  PRINT
150  FOR I = 1 TO N
160  INPUT X(I),Y(I)
170  NEXT I
180  PRINT : PRINT
190  REM   *** CALCULATIONS  ***
200  FOR I = 1 TO N
210 X(I) =  LOG (X(I))
212  IF Y(I) = 100 THEN 225
220 Y(I) = 100 / (100 - Y(I))
224  GOTO 230
225 Y(I) = 1E28
230 Y(I) =  LOG (Y(I)):Y(I) =  LOG (Y(I))
240  NEXT I
390  REM
400  REM   ***  LINEAR REGRESSION SUBROUTINE  ***
405 A = 0:B = 0
410  FOR I = 1 TO N
420 SX = A + X(I)
430 SY = B + Y(I)
440 A = SX:B = SY
450  NEXT I
460 AX = SX / N
470 AY = SY / N
480 A = 0:B = 0:C = 0
490  FOR I = 1 TO N
500 S1 = A + X(I) * Y(I)
510 S2 = B + X(I) ^ 2
520 S3 = C + Y(I) ^ 2
530 A = S1:B = S2:C = S3
540  NEXT I
550 SL = (S1 - N * AX * AY) / (S2 - N * AX ^ 2)
560 IN = AY - SL * AX
565 D50C =  EXP (( LOG ( LOG (2)) - IN) / SL)
```

```
570  PRINT
580  REM  ***OUTPUT  RESULTS ***
590  PRINT  CHR$ (4);"PR#1"
600 E$ = "THE SLOPE,M       D50(C),MICRONS"
610 B$ = "#.######          ####.###  "
620  PRINT
625  PRINT E$
630  &  PRINT USEB$;SL,D50C
640  PRINT
650  PRINT  CHR$ (12)
660  PRINT
670  PRINT  CHR$ (4);"PR#0"
680  END
```

# APPENDIX IV

# CALCULATION PROGRAM

```
100  REM
110  REM  *** PROGRAM NAME: AIV.1 ***
120  REM
130  REM  *** PROGRAM TO CALCULATE RF,EAAND ***
140  REM  *** EC USING EXPERIMENTAL DATA    ***
150  REM  *** ON SPIRAL CLASSIFIER O/F & SAND ***
160  REM
170  REM  *** SPECIFICATION OF VARIABLES ***
180  REM  *** AND PARAMETERS ***
190  REM  EA(I)=ACTUAL EFFICIENCY IN THE ***
200  REM  *** ITH SIZE FRACTION          ***
210  REM  *** EC(I)=CORRECTED EFFICIENCY ***
220  REM  *** IN THE ITH SIZE FRACTION   ***
230  REM  *** XD(I)=PARTICLE SIZE IN THE ***
240  REM  *** ITH SIZE FRACTION          ***
250  REM  *** F1(I)=% WT. OF ITH SIZE    ***
260  REM  *** FRACTION IN THE O/F        ***
270  REM  *** F2(I)=% WT.OF THE ITH SIZE ***
280  REM  *** FRACTION IN THE SANDS ***
290  REM  *** A=SLURRY WEIGHT (KG/MIN.)  ***
300  REM  *** IN THE SANDS               ***
310  REM  *** B=SOLID WEIGHT IN THE SAND ***
320  REM  *** C=SLURRY WEIGHT IN THE O/F ***
330  REM  *** D=SOLID WEIGHT IN THE O/F  ***
340  DIM EA(10),EC(10),XD(10),F1(10),F2(10)
350  DIM OF(10),SA(10),CF(10),R(10),CR(10)
360  READ N
370  DATA  8
380  REM
390  REM  ****CALCULATE RF ***********
400  PRINT "INPUT A,B,C,D"
410  INPUT A
420  INPUT B
430  INPUT C
440  INPUT D
450 W1 = A - B
460 W2 = C - D
470 RF = W1 / (W1 + W2)
480 RF = RF * 100
490  REM
500  REM
510  REM  ******CALCULATE EA ************
520  FOR I = 1 TO N
530  READ XD(I),F1(I),F2(I)
540  NEXT I
550  DATA   2803, 0,     0.09
560  DATA   992,  2.48,  30.16
```

```
570  DATA   350,  2.27,  16.27
580  DATA   248,  8.19,  14.27
590  DATA   174,  6.49,   7.76
600  DATA   104,  4.89,   4.18
610  DATA   63,  20.93,   9.37
620  DATA   -63, 54.75,  17.90
630  FOR I = 1 TO N
640 OF(I) = D * F1(I)
650 SA(I) = B * F2(I)
660  NEXT I
670  FOR I = 1 TO N
680 CF(I) = OF(I) + SA(I)
690  NEXT I
700  FOR I = 1 TO N
710  IF CF(I) = 0 THEN 740
720 EA(I) = SA(I) / CF(I)
730 EA(I) = EA(I) * 100
740  NEXT I
750  FOR I = 1 TO N
760 CR(I) = CF(I) / (G + H)
770  NEXT I
780  REM
790  REM
800  REM  ******CALCULATE EC **********
810  FOR I = 1 TO N
820  IF EA(I) = 0 THEN 850
830 EC(I) = (EA(I) - EA(N)) / (100 - EA(N))
840 EC(I) = EC(I) * 100
850  NEXT I
860  REM
870  REM
880  REM  ******** OUTPUT RESULTS ********
890  PRINT  CHR$ (4);"PR#1"
900  PRINT : PRINT : PRINT : PRINT
910  FOR I = 1 TO 64
920  PRINT "X";
930  NEXT I
940  PRINT : PRINT : PRINT
950  PRINT  TAB( 20);"RESULTS OF CALCULATIONS"
960  PRINT  TAB( 20);"************************"
970  PRINT
980 E$ = "SIZE     DISTRIBUTION      EA      EC"
990 A$ = "MICRO.   O/F      SAND      %       % "
1000 B$ = "####    ###.##   ###.##   ###.## ###.##"
1010  PRINT E$
1020  PRINT A$
1030  PRINT
1040  FOR I = 1 TO N
```

```
1050  &  PRINT USEB$;XD(I),F1(I),F2(I),CR(I),EA(I),EC(I)
1060  NEXT I
1070  PRINT : PRINT
1080  PRINT "RF=";RF
1090  PRINT  CHR$ (12)
1100  PRINT
1110  PRINT  CHR$ (4);"PR#0"
1120  END
```

```
100  REM
110  REM  *** PROGRAM NAME: AIV.2 ***
120  REM
130  REM  *** PROGRAM TO CALCULATE D50C,
140  REM      RF,FZ AND MM USING THE
150  REM      SPIRAL CLASSIFIER MODEL ***
160  REM
170  REM
180  DIM X1(50),X2(50),X3(50),X4(50),X5(50)
190  DIM X6(50),RF(50),FZ(50),D50(50),MM(50)
200  DIM A(50),B(50),C(50),D(50),E(50),G(50)
210  DIM H(50),L(50),P(50),T(50),U(50),V(50),W(50)
220 M$ = "TOT.DATA"
230  PRINT  CHR$ (4);"OPEN";M$
240  PRINT  CHR$ (4);"READ";M$
250 N = 46
260  FOR I = 1 TO N
270  INPUT X1(I),X2(I),X3(I),X4(I),X5(I)
280  INPUT X6(I),RF(I),FZ(I),D50(I),MM(I)
290  NEXT I
300  PRINT  CHR$ (4);"CLOSE";M$
310  FOR I = 1 TO N
320 A(I) = .16387 * X2(I) + 0.00361 * X3(I) * X3(I) +
0.00009 * X4(I) * X4(I)
330 B(I) = 0.0099 * X1(I) * X2(I) - 0.00414 * X2(I) * X3(I)
- 0.3634
340 D50(I) =  EXP (A(I) + B(I))
350  NEXT I
360  FOR I = 1 TO N
370 D(I) = 0.00336 * X1(I) * X1(I) - 0.00117 * X1(I) * X5(I)
+ 4.70739
380 E(I) = 0.01486 * X3(I) * X6(I) - 0.00389 * X5(I) * X6(I)
390 C = 0.000001 * X5(I) * X5(I) * X5(I)
400 RF =  EXP (C(I) + D(I) + E(I))
410  NEXT I
420  FOR I = 1 TO N
430 G(I) = 1.7429 * X1(I) + 1.2272 * X4(I) + 0.03768 * X1(I)
* X3(I) - 19.34232
440 H(I) =  - 0.018315 * X1(I) * X5(I) + 0.015492 * X2(I) *
X4(I)
450 L(I) =  - 0.010625 * X3(I) * X5(I) + 0.068742 * X3(I) *
X6(I)
460 P(I) =  - 0.12669 * X4(I) * X6(I) + 0.944E - 05 * X5(I)
* X5(I) * X5(I)
470 RF(I) = G(I) + H(I) + L(I) + P(I)
480  NEXT I
490  FOR I = 1 TO N
```

```
500  REM
510  FOR I = 1 TO N
520 T(I) = 0.089438 * X4(I) - 0.000015 * X4(I) * X4(I) *
X4(I) - 1.515645
530 U(I) = 0.001812 * X3(I) * X3(I) - 0.001144 * X1(I) *
X2(I)
540 V(I) = 0.657891 *  LOG (X1(I) * X6(I)) - 1.194772 *  LOG
(X3(I))
550 W(I) = 0.058442 * X1(I)
560 MM(I) = T(I) + U(I) + V(I) + W(I)
570  NEXT I
580  REM
590  REM  *** OUTPUT OF RESULTS ***
600  PRINT  CHR$ (4);"PR#1"
610  PRINT : PRINT : PRINT
620  PRINT  TAB( 20);"THE VALUE OF D50,RF,FZ,MM"
630  PRINT  TAB( 4);" *************************"
640  PRINT
650 E$ = "NO.OF TEST  D50C    RF    FZ    MM"
660 B$ = "  ##       ####.##  ###.#  ###.# ###.#"
670  PRINT E$
680  PRINT
690  FOR I = 1 TO N
700  &  PRINT USEB$;D50(I),RF(I),FZ(I),MM(I)
710  NEXT I
720  PRINT : PRINT
730  PRINT  CHR$ (4);"PR#0"
740  END
```

```
100  REM
110  REM  *** PROGRAM NAME: AIV.3          ***
120  REM
130  REM  *** PROGRAM TO MAKE A DATA FILE ***
140  REM  *** FOR ALL TEST DATA           ***
150  REM
160  DIM X1(50),X2(50),X3(50),X4(50),X5(50)
170  DIM X6(50),RF(50),FZ(50),D50(50),MM(50)
180 N = 46
190  FOR I = 1 TO N
200  READ X1(I),X2(I),X3(I),X4(I),X5(I)
210  READ X6(I),RF(I),FZ(I),D50(I),MM(I)
220  NEXT I
230  DATA
10.99,42.1,23.35,33.8,135,10.9,10.59,7.41,126.27,1.1
240  DATA
11.27,40.33,22.41,35.43,135,10.9,8.43,7.1,115.24,1.16
250  DATA
10.69,41.34,20.47,36.63,135,10.9,9.22,7.52,169.02,1.37
260  DATA
9.53,42.8,23.39,28.29,183,13,54.6,15.64,103.15,0.79
270  DATA
7.87,47.34,22.52,28.15,183,13,47.9,17.9,144.88,1.03
280  DATA
9.28,43.72,25.52,25.3,183,13,38.85,15.17,176.67,1.24
290  DATA
23.51,41.58,33.11,27.27,135,13,7.91,4.66,292.14,2.28
300  DATA  6.52,62,32.15,30.17,135,13,9.33,7.23,255.69,1.41
310  DATA
11.88,55.23,38.26,27.83,183,10.9,23.05,9.58,321.3,2.18
320  DATA
11.58,53.86,28.64,29.11,183,10.9,35.92,14.61,344.57,1.48
330  DATA
9.58,58.34,33.61,27.79,183,10.9,26.78,13.15,322.14,1.57
340  DATA
16.26,56.92,28.33,28.49,183,10.9,21.92,16.14,456.38,1.67
350  DATA
17.87,50.19,23.89,29.41,183,10.9,23.71,17.92,412.84,1.29
360  DATA
14.93,53.23,12.75,38.84,135,13,2.42,5.4,1003.92,1.48
370  DATA
15.34,50.62,13.05,39.47,135,13,2.05,7.44,1099.03,1.52
380  DATA
10.39,53.68,38.55,24.91,183,13,18.78,6.76,376.39,2.3
390  DATA  10.55,12.4,75,20.04,183,13,20.08,6.31,416.65,1.49
400  DATA
13.42,54.04,19.46,28.84,135,10.9,10.32,6.63,631.75,1.45
```

```
410  DATA
15.38,46.69,29.91,23.86,183,13,8.16,5.39,397.11,1.71
420  DATA  28.2,43.23,22,29.92,183,13,4.72,5,600.49,2.14
430  DATA
21.04,47.4,11.44,37.01,135,10.9,2.85,5.62,804.28,2.43
440  DATA
21.81,47.5,10.74,36.23,135,10.9,2.93,6.65,844,2.24
450  DATA
18.68,47.3,15.4,32.79,183,10.9,27.41,20.66,406.93,1.23
460  DATA
21.55,46.19,20.42,26.26,183,10.9,21.95,10.68,380.08,1.57
470  DATA
21.34,47.16,9.64,35.74,135,13,2.3,4.07,731.33,2.73
480  DATA
19.42,44.5,8.66,33.51,135,13,1.91,4.02,793.68,2.36
490  DATA
18.68,56.64,12.49,35.59,163,13,2.06,9.53,1917.53,1.15
500  DATA
20.28,58.6,15.85,35.55,163,10.9,7.2,18.87,1794.43,1.42
510  DATA
22.93,56.27,12.84,31.79,135,10.9,2.92,15.36,2410.24,1.5
520  DATA
13.64,55.76,15.3,35.62,183,13,9.65,18.63,1448.57,1.96
530  DATA
7.98,46.65,25.9,47.6,135,10.9,10.42,8.42,205.44,1.57
540  DATA
19.61,39.75,17.1,51.74,183,13,5.07,8.15,226.23,1.93
550  DATA
15.78,37.1,11.32,56.65,135,13,3.06,7.68,267.82,2.08
560  DATA
16.31,38.85,13.28,53.36,183,10.9,21.22,29.01,216.53,1.88
570  DATA
9.69,54.44,19.83,43.13,183,10.9,80.49,40,319.1,1.22
580  DATA  18.09,54.82,
9.82,54.94,135,13,1.51,20.11,2522.74,1.58
590  DATA
10.42,55.62,13.25,51.97,183,13,6.42,32.12,2638.57,1.58
600  DATA
10.17,55.97,13.49,51.62,135,10.9,8.64,32.13,1935.55,1.29
610  DATA
16.94,44.04,18.29,53.06,183,13,7.26,11.77,275.01,2.23
620  DATA
28.32,42.13,7.32,61.47,135,10.9,2.48,14.83,894.16,2.12
630  DATA
11.37,48.99,27.17,44.61,183,10.9,40.57,28.39,240.05,1.83
640  DATA
18.36,41.91,7.48,61.85,163,13,2.04,10.59,579.69,2.18
650  DATA
```

```
21.19,58.03,20.97,42.31,135,13,4.1,10.48,1218.29,1.75
660  DATA
12,55.47,15.18,50.65,183,10.9,63.61,46.88,953.45,1.02
670  DATA
16.25,56.74,15.14,47.54,135,10.9,11.99,30.36,1356.24,2.3
680  DATA
17.24,53.07,14.31,49.83,183,13,7.64,28.91,1562.63,1.83
690  PRINT "NAME OF THE FILE"
700  INPUT M$
710  PRINT  CHR$ (4);"OPEN";M$
720  PRINT  CHR$ (4);"DELETE";M$
730  PRINT  CHR$ (4);"OPEN";M$
740  PRINT  CHR$ (4);"WRITE";M$
750  FOR I = 1 TO N
760  PRINT X1(I)
770  PRINT X2(I)
780  PRINT X3(I)
790  PRINT X4(I)
800  PRINT X5(I)
810  PRINT X6(I)
820  PRINT RF(I)
830  PRINT FZ(I)
840  PRINT D50(I)
850  PRINT MM(I)
860  NEXT I
870  PRINT  CHR$ (4);"CLOSE";M$
880  END
```