A DENSE MEDIUM CYCLONE MODEL FOR SIMULATION

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ABSTRACT

The dense medium cyclone model described in this paper is based on the observation that size-by-size partition curves generally "pivot" about a single point, which can be defined by two parameters: the pivot density and the pivot partition number. The pivot point is in turn correlated with the proportion of medium reporting to underflow. An expression is developed for the partition curve, incorporating three parameters - the two pivot parameters and the $E_p$. These parameters are then determined as functions of operating and design variables.

Two realisations of the model are presented: one based on a pilot study with a 200 mm cyclone, and one based on a field study of 200 mm and 400 mm cyclones at Mount Isa. Aspects considered include the effect of cyclone diameter, crowding due to high throughputs and the prediction of product medium densities using a classification model. The cyclone model requires refinement and validation, and plant surveys are planned to achieve this. A preliminary model form will be available in JKSimMet early in 1990.
1. **INTRODUCTION**

Despite 50 years of development, no generally available quantitative model of dense medium cyclones exist today. The Dutch State Mines organisation developed design procedures based on its large body of operating data, but DSM have never published a cyclone model. The post-war English language literature contains about 50 papers dealing with attempts to understand the principles of DM cyclone operation, but in none of these is a predictive model advanced which has survived into general use. Recent work at the JKMRC has resulted in a preliminary predictive model of DM cyclone performance, but this is at present confined to coal washing applications (Davis, 1987; Wood *et al*, 1987).

A research programme was therefore initiated to gather data on cyclone performance, both from operating plants and from pilot plant testwork, in order to formulate a general mathematical description of steady state size-by-size partitioning in the DM cyclone. The ultimate objective was to produce a model that could be used in simulation to predict the metallurgical performance of a given unit, from the design and operating conditions. It was intended that the model be of general form and therefore ultimately applicable both to low density separations (coal, using magnetite media) and high density separations (minerals, using ferrosilicon media). This paper describes the significant progress which has been made towards this goal. The details may be found in Scott (1988).

2. **MODEL STRUCTURE**

Any two-product gravity concentration process is completely described by the *partition curve* (Figure 1), which defines the proportion of feed particles of a given size and density which reports to one or other product (by convention, usually the sinks or underflow product). The development of an effective DM cyclone model therefore resolves itself into two components: finding an appropriate descriptor of the partition curve itself, and developing a method of predicting the parameters of that descriptor from a knowledge of the design and operating variables which can be measured and/or controlled. Once the partition curve is predicted from the system variables, the curve can then be multiplied by the (known) feed washability to predict the complete metallurgy of the separation.
Figure 1: Typical partition curves showing the pivot parameters, \( Y_p \) and \( \rho_p \), the ecart probable, \( E_p \), and the separation density, \( \rho_{50} \)

2.1 THE PARTITION CURVE

The present work utilises an equation for the partition curve derived from a general expression for classification proposed by Whiten, and used subsequently by many workers in both classification and density separation. Whiten's expression (for density separations) is:

\[
Y_j = \frac{\exp(\alpha \rho_j/\rho_{50}) - 1}{\exp(\alpha \rho_j/\rho_{50}) + \exp(\alpha) - 2}
\]  

where \( Y_j \) is the weight fraction of density species \( \rho_j \) in the feed which reports to underflow, \( \rho_{50} \) is the separating density, and \( \alpha \) is an efficiency parameter (high values of \( \alpha \) indicating sharp partition curves).

It can be shown (Rong & Lyman, 1985) that for DM cyclones, \( \alpha \) will usually exceed 4. In such cases, Equation 1 can be simplified to:

\[
Y_j = \frac{1}{1 + \exp[\alpha (\rho_{50} - \rho_j)/\rho_{50}]} 
\]  

This is the partition curve equation.
2.2 THE PIVOT PHENOMENON

In considering the fundamentals of DM cyclone behaviour, Napier-Munn (1980, 1984) pointed out that for media consisting of pure liquids or neutrally buoyant suspensions, particles of density equal to that of the medium must partition to overflow and underflow in the same proportion as the medium. This phenomenon is exactly analogous to the "bypass" of water-borne fines to a hydrocyclone underflow product.

Scott (1988) re-presented Napier-Munn's experimental data to demonstrate that this principle resulted in size-by-size partition curves all passing through the same point, defined by the medium density and the proportion of medium reporting to underflow, Rm (Figure 2). Scott defined this point as the pivot point, and referred to this behaviour as the pivot phenomenon.

A more surprising result inferred from the literature was that even size-by-size partition curves from cyclones operating with conventional unstable media appeared to exhibit the pivot phenomenon (Figure 3), despite the thickening of the medium which occurred and the corresponding difficulty of defining a pivot point theoretically.

![Figure 2: Size-by-size partition curves: Plastic viscosity 9.2x10^{-3} Nsm^{-2} (after Napier-Munn, 1980)](image-url)
Scott therefore proposed that the pivot phenomenon was a fundamental feature of DM cyclone behaviour, and could be used as the basis of a general model of the process. The phenomenon was incorporated into the partition model (Equation 2) as follows:

For high values of \( \alpha \), as in the case of DM cyclones, it can be shown that the \( E_p \) (Figure 1) can be expressed as:

\[
E_p = \frac{1.099 \rho_{50}}{\alpha}
\]  

(3)

Substitution of Equation 3 into Equation 2 yields:

\[
Y_{ij} = \frac{1}{1 + \exp \left[ \frac{1.099(\rho_{50} - \rho_j)}{E_p} \right]}
\]  

(4)

The pivot point is completely described by 2 parameters (Figure 1):

- \( Y_p \) - the pivot partition number (%)
- \( \rho_p \) - the pivot density (kg m\(^{-3}\)).

It is well known from observation that there is in practice a relationship between \( E_p \) and \( \rho_p \) for a particular system, \( E_p \) increasing with \( \rho_p \).

One of the central propositions of this work is that the relationship between the \( \rho_{50} \) and \( E_p \), which it should be remembered are empirical and arbitrary curve parameters, exists due to the fact that all partition curves regardless of size must pass through a point defined by the pivot parameters \( Y_p \) and \( \rho_p \). The \( E_p \) represents the slope of the efficiency curve measured between the 25% and 75% partition numbers. It is equally valid to measure the slope using the \( Y_p \) and 50% partition numbers, and consequently if the \( E_p \) increases, the term \( (\rho_p - \rho_{50}) \) must also increase. This fact can be expressed mathematically by substituting for \( Y_p \) and \( \rho_p \) into Equation 4 and rearranging (Scott, 1985):

\[
E_p = \frac{1.099 (\rho_{50} - \rho_p)}{\ln \left[ (1 - Y_p)/Y_p \right]}
\]  

(5)

If Equation 5 is substituted into Equation 4 in order to eliminate \( \rho_{50} \) the following expression results:

\[
Y_{ij} = \frac{1}{1 + \exp \left[ \ln \left( Y_p^{-1} - 1 \right) + 1.099(\rho_p - \rho_{50})/E_p \right]}
\]  

(6)
The partition number for a particle of size (i) and density (j) can therefore be determined knowing only the value of the pivot parameters and the \( E_p \) for each particle size. Given a set of size-by-size partition data for a particular cyclone survey, the values for \( Y_p, \rho_p \) and \( E_p \) can be determined by non-linear regression.

Equation 6 then represents the basic model structure. The remainder of the research was devoted to confirming the existence of the pivot phenomenon experimentally, determining its properties, and establishing correlations for the parameters in Equation 6 in terms of system variables.

3. EXPERIMENTAL OUTLINE, AND RESULTS

3.1 PILOT PLANT TESTWORK

The objectives of the experiments conducted on the JKMRC pilot plant were to examine the consistency of the pivot phenomenon over a wide range of operating conditions, and to test the hypothesis that the pivot parameters are physically related to the properties of the medium pulp. An experimental grid was conceived in which the independent variables were apex diameter and medium pulp viscosity. A molasses/water solution was used as the medium liquor, the viscosity of which could be altered by adjusting the concentration of the molasses without affecting significantly the medium density.

The dense medium cyclone used was 200 mm in diameter and could be fitted with three different apex pieces of equivalent diameter 0.3Dc, 0.35Dc and 0.4Dc. The other cyclone dimensions conformed to standard DSM design. At certain points on the experimental grid, surveys were conducted on both 200 mm and 100 mm cyclones of identical geometry. Both cyclones were gravity fed.

Medium viscosity was measured using a Debex on-line viscometer (Reeves, 1985). Two different -2 mm "ore" types were employed, at volumetric medium-to-ore ratios in excess of 50.1:

1. Crushed and colour-coded plastic was used to determine cyclone separation efficiency at feed medium densities below 2000 kg.m\(^{-3}\).

2. Mt Isa lead-zinc ore was used for surveys conducted at densities greater than 2000 kg.m\(^{-3}\).
Flowrates were determined for each product, and samples taken to determine the partitioning of both ore and medium. Heavy liquid separation and point counting were used to analyse the ore separation. The medium solids were Samancor 150D ferrosilicon.

The data were mass balanced, and the ore partition data were fitted to the partition curve function, Equation 4, by non-linear least squares procedures. When the fitted size-by-size curves were plotted, it was apparent that the pivot phenomenon was present in most tests (Figure 3). The data were then re-fitted to the pivot function, Equation 6, which constrains the size-by-size curves to pivot. Statistical tests indicated that the increase in the amount of data adjustment which accompanied the imposition of the pivot constraint was usually not significant. It was therefore concluded that the pivot phenomenon could be included in the representation of DM cyclone performance.

3.2 INDUSTRIAL TESTWORK

The industrial surveys were conducted at the Mount Isa Mines Ltd preconcentrator, details of which can be found in Munro et al (1982). The preconcentrator incorporates 400 mm DSM design cyclones which are gravity fed by an 8 m head, compared with the 200 mm cyclones fed by a 3.2 m head used in the pilot plant study. Some tests were conducted on 200 mm cyclone installed in parallel with a 400 mm module. Medium-to-ore ratios for the industrial testwork averaged 9:1 which, based on the estimated cyclone throughput equivalent to an 8 m head, represented feed ore tonnages of 11 tph and 60 tph for a 200 mm and 400 mm cyclone respectively. For comparison, pilot plant medium-to-ore ratios for the 200 mm cyclone were approximately 65:1, representing a feed rate of 0.9 tph.

The influence of viscosity (again measured using a Delux viscometer) was studied by replacing the entire contents of one medium circuit with clean 150D ferrosilicon. Over a period of time, ingress of pyrrhotite from the fresh feed ore into the medium circuit contaminated the medium and increased its viscosity. By judiciously timing the execution of cyclone surveys, utilise natural variations in viscosity whilst holding the feed medium density relatively constant in the region of 3000 kg.m\(^{-3}\).
Figure 3: Typical size-by-size partition data showing fitted curves for individual size fractions passing through observed data points
Twelve surveys were conducted over a seven-day period on occasions that were dictated by the value of the medium viscosity, which was monitored continuously. Feed medium densities were in the range 2600 - 3025 kg.m$^{-3}$, and medium to ore ratios in the range 5.6 - 13.6. Timed product samples were taken, and the ore and medium separated by screening. Ore samples were processed in heavy liquids down to 0.25 mm. Medium solids were analysed for size distribution.

The data were mass balanced and the partition curves fitted as before. Figure 4 shows typical size-by-size partition curves for the ore, for sizes in the range 0.25 - 4.76 mm, which have not been constrained to pivot.

4. NUMERICAL MODELS FOR THE PARTITION CURVE

4.1 THE PILOT STUDY - A MODEL OF A 200 MM CYCLONE

The Correlation between $Y_p$ and $R_m$

The values of the pivot partition number obtained from curve fitting using Equation 6 were compared with the volumetric flow split of medium pulp to the underflow in order to test the assumptions made regarding the physical significance of the pivot phenomenon. Figure 5 plots $Y_p$ versus $R_m$ for the fifteen 200 mm cyclone surveys conducted using crushed plastic density tracer in the feed density range 1400 to 1800 kg.m$^{-3}$.

![Figure 5: The correlation between $Y_p$ and $R_m$ for cyclone surveys using crushed plastic density tracer](image-url)
One would expect a correspondence between $Y_p$ and $R_m$ for a stable medium (Napier-Munn, 1980). Examination of the present data showed that such a correspondence does exist even for unstable media, but only at low operative differentials (below 400 kg m$^{-3}$). At higher differentials the pivot partition number is systematically higher than the preparation of medium reporting to underflow.
Choosing a separation parameter

In considering DMC performance it is usual to quote the prevailing $P_{50}$ and $E_p$. One or other of these (but not both) is necessary to define the partition curve function incorporating the pivot parameters.

The literature has many references to the observation that $\rho_{50}$ is correlated with $E_p$; as the separating density increases, the $E_p$ also increases (i.e. the quality of separation deteriorates) regardless of the system characteristics. There is however no explicit physical justification for such a relationship to exist other than that due to the pivot phenomenon constraint. From examination of Figure 1, it can be seen that if the pivot parameters are fixed then an increase in the slope of the partition curve, the $E_p$, must always cause the $\rho_{50}$ to increase. Hence the $E_p$ increases with $\rho_{50}$ for a constant $R_m$, and if for a constant $\rho_{50}$, $R_m$ increases, so also will the $E_p$.

When using the partition curve model (Equation 6), the dense medium partitioning process can thus be characterised using the two pivot parameters, $Y_p$ and $\rho_{50}$, and either one $E_p$ or $\rho_{50}$ for each size fraction (i) of interest. Both the $E_p$ and $\rho_{50}$ are empirical curve parameters, and mathematically no difference results from choosing either one or the other for the partition curve model.

The $E_p$ has the advantage both of being a de facto industry standard, and providing a systematic measure of the relationship between separation efficiency and particle size. Figure 6 shows the well-known trend of $E_p$ increasing rapidly as the finer particle sizes.

Modelling the $E_p$, and Development of the 4-parameter Partition Curve Model

It was proposed that the relationship between $E_p$ and particle size, $d_i$, could be described by the expression

$$E_{pi} = k d_i^n$$

(9)

The proportionality constant contains implied terms for acceleration, viscosity and other system variables and the size exponent $n$ will vary between -1.0 and -2.0 for fully laminar and fully turbulent flow conditions respectively. The data confirmed that Equation 9 was appropriate, but with varying values of $n$, corresponding to a variation in the prevailing particle Reynolds number; most particle Reynolds numbers were estimated to fall in the intermediate flow regime. The best estimate of $n$
for all twenty 200 mm cyclone pilot plant surveys was -1.32; it was not possible to show with any statistical confidence that \( n \) varied in any systematic (modellable) way, and a constant value of -1.32 was therefore adopted for the pilot plant work.

![Graph of Ep vs. particle size for different apex diameters](image)

**Figure 6**: The effect of particle size on Ep for three apex diameters and a constant pulp density and viscosity

The coefficient \( k \) was predicted from the following regression equation:

\[
\ln(k) = 11.6 + 1.40 \ln(\mu) + 2.5 \ln(D_u/D_c)
\]

\( R^2 = 0.93 \quad \text{Eq.Res.S.E.} = 0.31 \quad \text{NDP} = 20 \)

Here, \( \mu \) is the medium viscosity, and \( D_u \) and \( D_c \) are the apex and cyclone diameters respectively. This expression implies that Ep increases with viscosity, which is a generally accepted trend.

Since Equation 9 was shown to be an acceptable descriptor for the Ep-size relationship, it became possible to incorporate this descriptor into the partition curve model, Equation 6, reproduced here for convenience:

\[
Y_{ij} \left( \frac{1}{1 + \exp\left[\ln(Y_p^{-1} - 1) + 1.099(\rho_p - \rho_{ij}) / Ep_j\right]} \right)
\]
Equation 6 was re-fitted to the partition data, with the four parameters, $Y_p$, $\rho_p$, k and n being fitted simultaneously. This 4-parameter model was found to fit the data well, though values for n were larger than those determined by linear regression using the $E_p$ versus particle size data, reflecting the difference in data weighting between the linear and non-linear regression methods. The parameter values determined from the 4-parameter model were those used in the subsequent modelling of the pilot plant data.

**Modelling the Pivot Partition Number, $Y_p$**

Linear regression analysis was conducted in order to quantify the effect of $V_f$ and the cyclone density differential, $\Delta \rho$, upon $Y_p$. The following equation resulted:

$$\ln \left( \frac{Y_p}{Rm} \right) = 0.30 + 3.30 \ln(1 - V_f) - 0.47 \times 10^{-3} \Delta \rho$$

(11)

$R^2 = 0.85$  Eq.Res.S.E. = 0.20  NDP = 20

The form of the independent variables was selected such that if either $V_f$ or $\Delta \rho$ went to zero, $Y_p = Rm$. Under such conditions the cyclone would be operating as if with a heavy liquid or neutral buoyant suspension instead of a conventional unstable medium.

In order to use Equation 11 for predicting $Y_p$, it was necessary to know the value of $Rm$. A review of the literature and dimensional reasoning suggested the form of Equation 12 presented below. Equation coefficients were again determined by linear regression:

$$\ln(Rm) = k_1 + k_2 \ln \left( \frac{D_u}{D_c} \right) + k_3 \ln \left( \frac{\mu}{\rho_f Q} \right)$$

(12)

$R^2 = 0.93$  Eq.Res.S.E. = 0.10  NDP = 20

where $k_1 = 8.63$, $k_2 = 3.59$ and $k_3 = 0.26$

Here $Q$ is the volumetric flowrate of medium, and $\rho_f$ the feed medium density.

The value of the constant, $k_3$ of 0.26 can be compared with 0.4 - 0.5 obtained by Napier-Munn (1980) and 0.12 obtained by Davis and Napier-Munn (1987). It is known that flow to the underflow increases as the
cyclone Reynolds number decreases, due to internal friction and loss of centrifugal head. Based on this fact, and on the calculated Reynolds numbers prevailing in each of these investigations, it can be inferred that the value for $k_3$ is dependent on the Reynolds number.

**Modelling the Pivot Density, $\rho_p$**

The relationship between the pivot, feed and underflow densities can be accurately predicted by the following regression equation:

$$\rho_p = -135 + 0.75 \, \rho_f + 0.32 \, \rho_u$$

(13)

$$R^2 = 0.99 \quad \text{Eq.Res.S.E.} = 56 \, \text{kg.m}^{-3} \quad \text{NDP} = 20$$

The form of Equation 13 accommodates the existence of a density gradient within the cyclone, caused by medium solids sedimentation. If for a constant feed medium density the underflow density increases, due for example, to a reduction in pulp viscosity, the pivot density also increases. Equation 13 is also of the same form as correlations for $\rho_{50}$ reported by other workers (e.g. Napier-Munn, 1984).

The equation is not altogether appropriate for prediction, as $\rho_u$ is itself a defendant variable and examination of the data also showed that both viscosity and the feed FeSi volume fraction ($V_f$) influenced the extent to which $\rho_p$ differed from $\rho_f$ due to the complex density gradients in the cyclone, and the effects of apex overloading.

A useful parameter in this regard was found to be the ratio of pivot density volume fraction ($V_{fp}$) to feed density volume fraction ($V_f$), defined as:

$$VFR_p = \frac{\rho_p - \rho_L}{\rho_f - \rho_L}$$

(14)

The following equation was developed to predict this quantity (after the exclusion of four data points for which measurements inaccuracies propagated adversely into the transformed variable).

$$\ln(VFR_p - 1) = -7.60 + 0.66 \ln(V_f) - 1.87 \ln(\mu)$$

(15)

$$R^2 = 0.76 \quad \text{Eq.Res.S.E.} = 0.54 \quad \text{NDP} = 11$$

This equation predicted the observed pivot density very well.
An Overall Model for the Pilot Plant Data

Equations 9, 10, 11, 12, 14 and 15 provide the correlations necessary to predict the partition curve (Equation 6) and thus the metallurgy of the separation. However, these correlations were determined (by linear regression) independently of one another, and there is often value in carrying out a simultaneous fit of all the data over all the model parameters (Kojovic, 1988). This was done using the model builder reported in Chapter 1, but the residual standard deviation was larger than expected. Further analysis showed that the \( \rho_p/\rho_f \) term was contributing excessive error. The overall fit was then re-run excluding this term, with the results shown in Table 1:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Operating condition coefficients</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \ln(Y_p) )</td>
<td>(+7.06) (+2.51) (\ln(1-V_f)) (+3.10) (\ln(D_u/D_c)) (-0.11\times10^{-2}\Delta \rho)</td>
</tr>
<tr>
<td>( \rho_p )</td>
<td>Not included in overall fitting.</td>
</tr>
<tr>
<td>( \ln(k) )</td>
<td>(+9.58) (+1.27) (\ln(\mu)) (+1.11) (\ln(D_u/D_c))</td>
</tr>
<tr>
<td>( n )</td>
<td>(-1.30)</td>
</tr>
</tbody>
</table>

Table 1: The Model Obtained from "Overall" Partition Curve Fitting

The form of this model differed from the linear regression models only to the extent that the \( D_u/D_c \) term in the \( Y_p \) equation was found to be more effective than the \( Y_p/R_m \) ratio for minimising the overall error. The apex diameter directly affected \( R_m \) and so use of the \( D_u/D_c \) term was physically justified. However, whether or not the improvement in the overall data S.D. due to the \( D_u/D_c \) was also due to a physical reason or was merely an artefact of the data could not be determined.

Clearly some method is still required for estimating \( \rho_p \), one of the fundamental model parameters (Equation 6). However, in practice the need to predict \( \rho_p/\rho_f \) with great accuracy is mitigated by the fact that most plants have automatic density control. Consequently, adjustments of the order of \( \pm 40 \text{ kg.m}^{-3} \) necessary to compensate for error in the predicted value of \( \rho_p \) can be easily corrected for by raising or lowering the feed medium density.

For the same reason, simulation studies using this overall model could be conducted by using a simple interpolation procedure to select the feed medium density necessary for the plant to reach its production objectives, as follows:
1. Estimate the value of the feed medium density using the cyclone model and washability data.

2. Calculate $\rho_p$, $Y_p$ and $k$ using values of $V_f$ and $\mu$ consistent with the feed medium density.

3. Partition the cyclone feed ore and calculate metallurgical performance.

4. Calculate the difference between target and actual plant performance criterion, estimate new feed medium density based on knowledge of feed ore washability.

The procedure could be repeated until the desired metallurgical performance was reached.

**Summary of 200 mm Cyclone Pilot Plant Models**

Two computational routes are available for simulation purposes:

1. Calculate the necessary quantities from the following equations (in the order given):

   $$\ln(k) = 11.6 + 1.40 \ln(\mu) + 2.5 \ln(D_u/D_c) \quad (10)$$

   $$E_{pi} = k.d_i^n \quad (9)$$

   $$n = -1.32$$

   $$\ln(Rm) = 8.63 + 3.59 \ln\left(\frac{D_u}{D_c}\right) + 0.26 \ln\left(\frac{\mu}{\rho_fQ}\right) \quad (12)$$

   $$\ln\left[\frac{Y_p}{Rm}\right] = 0.30 + 3.30 \ln(1 - V_i) - 0.47 \times 10^3 \Delta \rho \quad (11)$$

   $$VFR_p = \frac{\rho_p - \rho_l}{\rho_f - \rho_l} \quad (14)$$

   $$\ln(VFR_p - 1) = -7.60 + 0.66 \ln(V_i) - 1.87 \ln(\mu) \quad (15)$$

   $$Y_{ij} = \frac{1}{1 + \exp\left[\ln\left(Y_{p}^{-1} - 1\right) + 1.099(\rho_p - \rho_{ij})/E_{pi}\right]}$$

   (6)
The density differential term $\Delta \rho$ in Equation 11 is of course a dependent variable itself, and some value must be found for it in order to complete the computation. In practice, this can either be done from experience, from operating data, or by prediction from the medium classification model to be described later.

2. Use the overall model given in Table 1, and adopt the iterative procedure outlined above to calculate the feed medium density necessary to meet the required metallurgical criteria.

4.2 INDUSTRIAL STUDIES - MODELS OF 200 MM AND 400 MM CYCLONES

Modelling the Ep

The industrial data illustrated quite well the contrast in the effect which viscosity has on coarse and fine particles; coarse particle separation is almost unaffected by changes in viscosity, whereas the separation efficiency of fine particles declines as viscosity increases. Figures 7a and 7b show the viscosity-Ep relationship for the 4.76 x 3.16 mm and 0.71 x 0.5 mm ore respectively, for all the 200 mm and 400 mm cyclone surveys - the coarser material shows no correlation, whereas the correlation for the finer material is clear.

However, further analysis of the data revealed an additional effect on Ep attributed to particle crowding, which is present in cases where there exists a lot of near-gravity material and/or at high tonnages. Modelling this effect required the introduction of an additional Ep parameter, $z$, as follows:

$$Ep = z + k.d^n$$

Physically, $z$ represents the contribution to the Ep caused by internal crowding due to ore particle recirculation. Mathematically, the form of Equation 16 was appropriate in that the relative effect of $z$ would be most pronounced for coarse particles which have intrinsically small Eps but, according to the data, are most severely affected by internal crowding. The potential advantage of Equation 16 was that operation of a cyclone so as to eliminate the possibility of internal crowding would cause $z$ to equal zero, and the Ep model would then reduce to that representative of the intrinsic cyclone separation efficiency, as monitored in the pilot plant testwork.
Partition curve fitting was repeated for the industrial surveys using the Ep parameters, k, n and the new crowding parameter, z. It was rapidly perceived that the JKMRC non-linear fitting program NLF had difficulty fitting three Ep parameters to the relatively small number of size fractions for which Eps had been determined. Consequently, it was decided to make the n parameter constant and equal to -1.0.

Figure 7a: The effect of pulp viscosity on the Eps of 4.76 x 3.16 mm ore particles

Figure 7b: The effect of pulp viscosity on the Eps of 0.71x0.5 mm ore particles
Modelling the Crowding Parameter, $z$

The partition data were re-fitted in terms of Equation 16 in order to estimate $k$, $n$ and $z$. A model was then developed to quantify the effect of the cyclone operating conditions upon $z$. Figure 8 shows that $z$ increased as the cyclone density differential, $\Delta \rho$, became greater, which was expected based on the hypothesis that the value of $z$ was related to internal ore recirculation and crowding.

![Figure 8: The effect of the cyclone density differential on the crowding parameter, $z$](image)

Since feed rate fluctuations would affect the flow rate of near-gravity material to the cyclone, the volumetric medium to ore ratio, $V_{mo}$, was included with $\Delta \rho$ in the following regression equation, which was based on 200 mm and 400 mm industrial cyclone data:

$$z = 19.6 + 0.16 \Delta \rho - 6.3 \ V_{mo}$$  \hspace{1cm} (17)

$$R^2 = 0.75 \hspace{0.5cm} \text{Eq.Res.S.E.} = 21 \ \text{kg.m}^{-3} \hspace{0.5cm} \text{NDP} = 12$$

Thus, $z$ increased and the cyclone became more inefficient as the density differential and the feed rate of ore to the cyclone increased. Analysis showed that the predictions from Equation 17 carried large confidence intervals, and the utility of the equation is therefore limited to
confirmation that $z$ responds in a physically consistent manner to changes in the cyclone operating conditions.

Only five $z$ values were shown to be significantly different from zero, and they were from surveys representing the four highest density differentials, approximately 500 kg.m$^{-3}$ or greater, in the industrial data set. It was therefore concluded that for $\Delta \rho < 400$ kg.m$^{-3}$, internal crowding due to ore recirculation was probably not a serious or detectable problem, a result which confirms the findings of Davis (1987) for coarse particle coal separations.

**Modelling the Ep parameter, $k$**

The following model was developed in order to predict the $k$ parameter for the 400 mm and 200 mm industrial data:

$$\ln(k) = 6.87 + 0.59 \ln(\mu) + 0.30 \ln(D_c)$$

(18)

$$R^2 = 0.89 \quad \text{Eq.Res.S.E.} = 0.15 \quad \text{NDP} = 12$$

The predictions of Equation 18 were judged to be good.

**Modelling the Pivot Partition Number, $Y_p$**

Again, the industrial data suggested that the presence of a finite throughput of ore affected the prevailing value of $Y_p$. Values of $Y_p$ predicted from the pilot data correlation (Equation 11) were lower than those actually observed in the industrial surveys. $Y_p$ was strongly correlated with the proportion of medium reporting to underflow, and the following simple expression described the 200 mm and 400 mm industrial data quite well:

$$Y_p = 0.61 \, R_m$$

(19)

$$R^2 = 0.88 \quad \text{Eq.Res.S.E.} = 2.6\% \quad \text{NDP} = 12$$

**Modelling the Pivot Density, $\rho_p$**

The data indicated that values of the volume fraction ratio, VFR$_p$, for the 200 mm industrial cyclones were consistently higher than those of the high density pilot plant surveys. There were sufficient data within the
literature to assume that this effect was due to the higher inlet velocities for the industrial data. Davis, Wood and Lyman (1985) demonstrated that increasing the gravity head feeding a 200 mm cyclone resulted in an increase in the underflow pulp density, which was indicative of a greater amount of medium solids sedimentation. This was attributed to higher inlet and tangential velocities, associated with the higher cyclone throughput, caused by the increase in static head feeding the cyclone.

Accordingly, the feed volumetric flow rate, Q, was included with the pulp viscosity in Equation 20 in order to model VFR_p using the 11 pilot plant data sets previously employed, plus the four industrial 200 mm cyclone data sets:

$$\ln \left( \frac{V_p}{V_f} - 1 \right) = -1.59 + 0.73 \ln(V_f) - 1.52 \left[ \frac{\mu}{Q} \right]$$

$$R^2 = 0.61 \quad \text{Eq.Res.S.E.} = 0.57 \quad \text{NDP} = 15$$

An Overall Model for the Industrial Data

As before, best-fit model parameters were determined for all the industrial partition data simultaneously, resulting in the "overall" model equations given in Table 2:

Table 2: The Model Obtained from "Overall" Partition Curve Fitting

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Operating condition coefficients</th>
</tr>
</thead>
<tbody>
<tr>
<td>ln(Y_p)</td>
<td>+1.23 ln(RM) -0.10x10^-2Δρ</td>
</tr>
<tr>
<td>ρ_p</td>
<td>Not included in overall fitting.</td>
</tr>
<tr>
<td>ln(k)</td>
<td>+7.25 +0.66 ln(μ) +0.94 ln(D_c)</td>
</tr>
<tr>
<td>z</td>
<td>-706 -0.054 ρ_f +0.29 ρ_u</td>
</tr>
<tr>
<td>n</td>
<td>-1.50</td>
</tr>
</tbody>
</table>

Total number of degrees of freedom 459
Data S.D. 2.61
Unweighted RMS partition number adjustment residuals 7.0%

The same independent variables were represented in the individual partition curve parameter models, with the exception of (1-V_f) in the Y_p equation, and (D_u/D_c) in the k equation, two variables which remained relatively constant for the industrial data set. Model coefficients were
slightly different for reasons previously discussed, but always acted in the same sense. The value for \( n \) of -1.50 was similar in value to that for the pilot plant data of -1.30.

Again, \( \rho_p \) was excluded, and would have to be incorporated iteratively in any simulation, as described for the pilot plant model (Table 1).

High underflow densities were shown to be more significant than the value of the density differential in predicting values of the crowding parameter, \( z \), and minimising the partition number adjustment residuals. The underflow density and density differential are highly correlated, and both variables are indicative of the propensity of the cyclone to experience ore recirculation.

**Summary of Industrial 200/400 mm Cyclone Models**

As before, two computational routes are available for simulation purposes:

1. Calculate the necessary quantities from the following equations (in the order given):

   \[
   z = 19.6 + 0.16 \Delta \rho - 6.3 \text{ Vmo} \tag{17}
   \]

   \[
   \ln(k) = 6.87 + 0.59 \ln(\mu) + 0.30 \ln(D_c) \tag{18}
   \]

   \[
   E_{pi} = z + k.d_i^n \quad (n = -1.0) \tag{16}
   \]

   \[
   Y_p = 0.61 \text{ Rm} \tag{19}
   \]

   \[
   \ln \left[ \frac{V_p}{V_f} - 1 \right] = -1.59 + 0.73 \ln(V_i) - 1.52 \left[ \frac{\mu}{Q} \right] \tag{20}
   \]

   \[
   Y_{ij} = \frac{1}{1 + \exp \left[ \ln(Y_p^{-1} - 1) + 1.099(\rho_p - \rho_i)/E_{pi} \right]} \tag{6}
   \]

As noted for the pilot plant model, the density differential term \( \Delta \rho \) in Equation 17 is a dependent variable itself, and some value must be found for it in order to complete the computation. In practice, this can either be done from experience, from operating data, or
by prediction from the medium classification model described below.

2. Use the overall model given in Table 2, and adopt an iterative procedure to calculate the feed medium density necessary to meet the required metallurgical criteria.

5. PREDICTION OF THE PRODUCT MEDIUM DENSITIES

As noted earlier, the need to predict the product medium densities exists because $\Delta \rho$ is required in the prediction of the pivot partition number, $Y_p$. Additionally, high values of the density differential, $\Delta \rho$, can reduce separation efficiency due to internal ore recirculation. In simulating a particular installation, therefore, it would be desirable to calculate $\Delta \rho$ to flag potential separation problems.

Values of $\rho_o$ and $\rho_u$, normalised to $\rho_f$, are plotted in Figures 9a and 9b as a function of the pulp viscosity, for the pilot plant surveys (200 mm cyclone, 0.35Dc apex) and the industrial surveys (400 mm cyclone, 0.36Dc apex). The data show the expected trends, with normalised density tending to unity as the viscosity increases. The influence of viscosity is clearly strong and must be incorporated into any model of the medium behaviour.

![Figure 9a: The effect of pulp viscosity on the cyclone density differential (pilot plant data, 200 mm cyclone, 0.35Dc apex)](image-url)
The classification of the medium in the cyclone was monitored by determining the size distribution and mass flow rates of the ferrosilicon solids in the feed, overflow and underflow streams, and calculating partition numbers for each size interval in the usual way.

Whiten’s classification function was then fitted to the mass balanced data by non-linear procedures:

\[
    Y_i = C + (1-C) \left[ \frac{\exp \left( \alpha \cdot d_i / d_{50c} \right) - 1}{\exp \left( \alpha \cdot d_i / d_{50c} \right) + \exp (\alpha) - 2} \right]
\]  

(21)

where 
- \( d_i \) = geometric mean size for size fraction (mm)
- \( d_{50c} \) = corrected classification cut-size (mm)
- \( \alpha \) = efficiency (slope) parameter
- \( C \) = fraction of water reporting to underflow.

\( d_{50c}, \alpha \) and \( C \) are parameters to be fitted to data. Examples of the partition curves for the pilot plant 200 mm cyclone data are shown in Figure 10.
Once the classification of the medium and the proportion of water reporting to underflow can be predicted, then the product densities can easily be calculated. It is therefore necessary to be able to predict the values of the parameters in the classification function, Equation 21. The pilot plant 200 mm data were used for this purpose.

\( \alpha \) was found to exhibit no systematic trend, and the mean value, 2.75, was therefore taken. Linear regression models were developed to predict the other parameters. C was found to be a function of the viscosity and volume concentration of FeSi solids:

\[
\ln(C) = 4.05 + 0.29 \ln(\mu_p) - 0.090 \ln(V_f) - 1.87
\] (22)

\[ R^2 = 0.88 \quad \text{Eq.Res.S.E.} = 0.047 \quad \text{NDP} = 10 \]

The coefficient for viscosity was the same as that determined previously for models predicting the behaviour of \( R_m \). The coefficient for \( V_f \) was small but statistically significant, and consistent with the earlier discussion regarding competition for space at the apex.

Plitt (1976) noted that the solids content of the feed, \( V_f \), had the most effect on the \( d_{50c} \) and took the view that this was due to the influence of \( V_f \) on the "effective" pulp viscosity, \( \mu_p \). He proposed that it was for this reason that \( V_f \) was often present in empirical equations for predicting the \( d_{50c} \). The present data pertain to experiments for which \( \mu_p \) and \( V_f \) were decoupled, thereby making it possible to quantify independently the effect of each variable, as follows:

\[
\ln(d_{50c}) = 7.91 + 0.85 \ln(\mu_p) + 0.19 \ln(V_f)
\] (23)

\[ R^2 = 0.86 \quad \text{Eq.Res.S.E.} = 0.018 \quad \text{NDP} = 10 \]

The product medium densities can now be calculated from the predicted classification performance, and thus the differential \( \Delta \rho \) can be determined. Predicted values of \( \rho_u \) and \( \rho_o \) are compared with the actual values in Figures 11a and 11b. The agreement is seen to be excellent.

The fact that a classification model can be used to predict accurately the product medium densities is strong evidence for the hypothesis that classification is the principal mechanism which determines the segregation of medium in the cyclone, under the conditions investigated. This conclusion supports that of Davis (1987) who conducted a similar investigation for magnetite separation in coal washing DM cyclones.
Figure 10: Ferrosilicon solids classification curves for the 200 mm pilot plant cyclone
Underflow density can also be predicted directly from the operating conditions using the following regression equations:

Pilot plant data:

\[
[VFR_u - 1] = 0.43 \times 10^{-4} \mu_p^{1.52} \cdot V_f^{0.35} \cdot \left( \frac{D_u}{D_c} \right)^{-2.91}
\]  \hspace{1cm} (24)

Industrial data:

\[
[VFR_u - 1] = 0.015 \mu_p^{0.90}
\]  \hspace{1cm} (25)

The predictive accuracy of these equations was comparable to that of the classification model, but it should be noted that they do not incorporate head or flowrate, which are important variables in determining product densities.

![Graph](image.png)

Figure 11a: Observed versus predicted values for the underflow density
6. THE EFFECTS OF CYCLONE DIAMETER

THE APPROACH TO THE PROBLEM

Analysis of the effect of cyclone diameter upon performance was undertaken using pairs of surveys for which the only deliberate variation in operating conditions was cyclone diameter. These constituted five pilot plant surveys, for which 100 mm and 200 mm cyclone data were available, and four industrial surveys for which 200 mm and 400 mm cyclone data were collected. The pairs of cyclone data pertain to surveys that were conducted at the same time, both cyclones treating the same feed ore in the same dense medium.

The general consensus in the literature is that small cyclones are required in order to process fine ore. Fine particles separate less efficiently than coarse particles and the higher centrifugal forces generated within small diameter cyclones are needed to compensate for this. The data analysis conducted in this section examines this assumption by interpreting the effect of cyclone diameter on the pivot partition number, $Y_p$, and the $E_p$ parameter, k.

The four-parameter partition curve model (Equations 6 and 9) was fitted to the pilot plant data. For the industrial data, the four-parameter model
was used in conjunction with the crowding parameter, \( z \), the value of \( n \) being held constant at -1.0 as discussed earlier.

**MODELLING THE MEDIUM BEHAVIOUR**

The pairs of data illustrating only the effects of cyclone diameter show clearly that \( R_m \) decreases with increase in diameter, as shown in Figure 12.

Consequently, the five pairs of 100 mm / 200 mm pilot plant data were modelled using the cyclone Reynolds number as the only independent variable with which to account for the effect of cyclone diameter. The following expression resulted:

\[
\ln(R_m) = 6.43 - 0.28 \ln(Re)
\]

\[ R^2 = 0.96 \quad \text{Eq.Res.S.E.} = 0.06 \quad \text{NDP} = 10 \]

![Figure 12: The effect of cyclone diameter on \( R_m \). Lines are drawn between cyclone data pairs for which the predominant change in cyclone operating conditions was cyclone diameter itself.](image)

According to the analysis presented by Fontein, van Kooy and Leniger (1962) this effect is the result of a reduction in shear occurring within the cyclone and a consequent diminution of centrifugal head. It is the
pressure gradient due to the centrifugal head that causes medium to flow from the cyclone wall, where the pressure is high, to the vortex finder. Consequently, a reduction in centrifugal head leads to an increase in $R_m$. At the same time, gravity fed cyclones, for which the pressure drop is constant, will sustain an increase in throughput, $Q$, until the increase in friction losses compensates for the reduction in centrifugal head. This phenomenon was evident in the 200 mm cyclone pilot plant data, which showed a systematic increase in $Q$ as pulp viscosity increased. Linear regression analysis leads to the following expression:

$$\ln(Q) = 4.43 + 0.12 \ln \left( \frac{D_u}{D_c} \right) - 0.11 \ln(Re)$$  \hspace{1cm} (27)

$$R^2 = 0.95 \quad \text{Eq. Res. S.E.} = 0.02 \quad \text{NDP} = 20$$

The predictive quality of Equations 26 and 27 was good. Both expressions demonstrated the importance of the cyclone Reynolds number, which for the pilot plant cyclones was varied predominantly by cyclone diameter within data pairs, and by pulp viscosity and density between pairs. Together the expressions supported the notion that low Reynolds number operation reduced shear within the cyclone, decreased tangential velocities, and lead to a lower centrifugal head.

Based on the preceding discussion it was concluded that all other factors being equal, a reduction in cyclone diameter would influence the separation process in two ways:

1. The tangential velocity at a given radius would decrease due to lower Reynolds number flow conditions.

2. The separation would be constrained by the walls of the cyclone to occur at smaller cyclone radii.

Due to the fact that centrifugal acceleration is proportional to $V^2/r$, the two effects will tend to oppose each other, and depending upon their relative magnitudes, a reduction in cyclone diameter need not necessarily result in an increase in centrifugal separation efficiency.

**MODELLING THE Ep PARAMETER, k**

In considering the effects of diameter on $k$, it was clear that trends were apparent but were not systematic over all data sets. It was concluded that no simple relationship between cyclone diameter and efficiency exists.
The different results for the pairs of cyclone data however suggested the existence of an optimum Reynolds number of approximately 50,000, below which a reduction in cyclone diameter lead to deterioration in efficiency, and above which efficiency improved. (This result was roughly equivalent to that obtained by Fontein, van Kooy and Leniger (1962) who identified an optimum Reynolds number of approximately 40,000). Accordingly the data were split into two categories defined by cyclone Reynolds numbers above and below 50,000, and the following expressions developed by linear regression:

**For \( \text{Re} < 50,000 \)** (4x100 mm, 2x200 mm pilot plant, 2x200 mm industrial):

\[
\ln \left( \frac{k}{D_c} \right) = 26.6 + 0.50 \ln(V_f) - 1.84 \ln(\text{Re})
\]  

\( R^2 = 0.93 \quad \text{Eq.Res.S.E.} = 0.14 \quad \text{NDP} = 8 \)

**For \( \text{Re} > 50,000 \)** (1x100 mm, 3x200 mm pilot plant, 2x200 mm industrial, 4x400 mm):

\[
\ln \left( \frac{k}{D_c} \right) = 13.0 + 0.63 \ln(V_f) - 0.54 \ln(\text{Re})
\]  

\( R^2 = 0.98 \quad \text{Eq.Res.S.E.} = 0.23 \quad \text{NDP} = 10 \)

The joint use of these two expressions provides good predictions of \( k \) in terms of cyclone diameter.

**MODELLING THE PIVOT PARTITION NUMBER, \( Y_p \)**

Equation 30 is a correlation for \( Y_p \) in terms of cyclone diameter. A term for the volumetric feed medium to ore ratio, \( V_{mo} \), was included in the regression to account for the possible effect of ore feed rate:

\[
\ln(Y_p) = 3.60 - 1.14 \ln(D_c) - 3.99 \ln(V_f) - 0.45 \ln(V_{mo})
\]  

\( R^2 = 0.91 \quad \text{Eq.Res.S.E.} = 0.28 \quad \text{NDP} = 18 \)

The value of \( Y_p \) increases as cyclone diameter decreases due to the fact that more of the medium pulp reports to underflow. Consequently, the
overall efficiency of the separation increases as cyclone diameter decreases because size-by-size partition curves spread apart to a lesser extent. The following example illustrates this effect.

The overall $E_p$ for a 1.0x0.25 mm size fraction was computed for a 100 mm cyclone and a 400 mm cyclone by summing the $E_p$s for the three sub-fractions, 1.0x0.71 mm, 0.71x0.5 mm, 0.5x0.25 mm, which were calculated using the geometric mean particle size, $d$, and values of $k = 50$ and $n = -1.3$ in the expression:

$$E_p = 50 \, d^{-1.3}$$

(31)

It was assumed for the purpose of the example that the separation efficiency was the same for the 100 mm and 400 mm cyclones, and that the $E_p$s for the three size fractions were therefore 63, 100 and 388 kg.m$^{-3}$. Based on Equation 30, if the pivot partition number was 50% for the 100 mm cyclone then operating under exactly the same conditions, the pivot partition number for the 400 mm cyclone would be approximately 12.5%.

Three size-by-size partition curves were calculated for each cyclone using the preceding data and an arbitrary value for the pivot density in the partition curve model (Equation 6). The distribution of material with respect to size within the 1.0x0.25 mm fraction was assumed to be uniform, and the average of the partition numbers for the three curves therefore represented the overall partitioning process. The overall $E_p$ was computed using this method and for the 100 mm cyclone was found to be 125 kg.m$^{-3}$ compared with 188 kg.m$^{-3}$ for the 400 mm cyclone, representing a deterioration in efficiency of approximately 50% in the larger cyclone.

Consequently, it was concluded that the effect of smaller cyclone diameters to move the pivot partition number to values closer to 50% represented an improvement in efficiency since, under normal circumstances, the feed to a dense medium cyclone comprises a distribution of particle sizes. At the same time, this phenomenon makes the successful interpretation of the effects of cyclone diameter upon performance feasible only if closely sized, size-by-size partition curves are obtained. Without this information it is possible to confuse the effect of the pivot partition number with the effect of, for example, higher centrifugal separation forces.
DISCUSSION

Smaller cyclones caused Re to decrease in value. However, due to the adjustment of pulp viscosity for individual cyclone surveys it was possible by interpolation to compare the performance of two sizes of cyclone operating with the same Reynolds number. Viewed in this manner it could be inferred that for a constant Re, a reduction in cyclone diameter caused efficiencies to increase. This was due to the fact that centrifugal separation forces at the smaller radius were stronger, and were not attenuated by lower Reynolds number flow and lower internal shear rates.

It is concluded that the effect of cyclone diameter upon the separation efficiency depends on the magnitude of the effect of the Reynolds number, which is itself dependent on the prevailing flow regime. A smaller cyclone gives a higher separation efficiency in some circumstances, and lower efficiencies in others. In general, in the present work, for values of Re greater than 50,000 a reduction in diameter increased efficiency, and for Re less than 50,000 efficiency deteriorated.

7. THE EFFECT OF FEED ORE DENSITY DISTRIBUTION ON SEPARATION EFFICIENCY

Evidence of a feed ore density effect was obtained from the results of surveys conducted on a 400 mm cyclone at Argyle Diamond Mines, processing a diamondiferous ore whilst operating with a large density differential of 940 kg.m\(^{-3}\) (Scott, 1988b). The propensity of the ore to recirculate within the cyclone was demonstrated by timing the recovery of 15 mm cubic density tracers from the cyclone underflow stream, the only stream for which this was physically practical. The results confirmed the prolonged retention of near-gravity density tracers within the cyclone, which was consistent with the high density differentials under which the cyclones operated.

In order to examine the effect this might have upon separation efficiency, tracer and ore partition curves were determined for typical cyclone operation.
The data were well described by Equation 16 using an exponent value of \( n = -1.0 \) as shown below:

\[
E_p = 4 + 52.d^{-1.0}
\]

\[ R^2 = 0.98 \quad \text{Eq.Res.S.E.} = 5 \quad \text{NDP} = 7 \]

The expression obtained previously for the \( E_p \) parameter, \( k \), from the MIM industrial tests (Equation 18) was used to predict the value of \( k \) for the Argyle data, knowing that the pulp Debex viscosity was \( 14 \times 10^{-3} \text{ Nsm}^{-2} \) and the data pertained to a 400 mm diameter cyclone. Agreement between the predicted value of 59 and the actual value of 52, shown in Equation 32 for the Argyle data, was good.

However, the large density differential of 940 kg.m\(^{-3}\) and medium-to-ore ratio of 8:1 suggested that the crowding parameter, \( z \), should be larger than the value of 4 that was obtained for the Argyle data. The predicted value for \( z \) using Equation 17 was 121 kg.m\(^{-3}\). A discrepancy therefore existed between the performance of 400 mm cyclones processing lead-zinc ore, and those processing diamondiferous ore. The intrinsic efficiency represented by the \( k \) parameter was similar for both operations. However, it appeared that the diamond recovery cyclones did not incur the same loss of efficiency as those processing lead-zinc ore, caused by operating with large density differential. This fact was attributed to the extremely different washability characteristics of the two ores.

Only by 0.2\% by weight of the diamondiferous ore comprised near-gravity material, defined as material having a density \( \pm 100 \text{ kg.m}^{-3} \) of the pivot density, which was 3000 kg.m\(^{-3}\) for the Argyle data. For two lead-zinc ore industrial surveys manifesting large \( z \) parameter values, the equivalent quantities of near-gravity material were 18\% and 8\% respectively. The calculated flowrate of near-gravity diamondiferous material was approximately 120 kg per hour, compared with between 5 and 11 tons per hour for the lead-zinc ore. Consequently, the rate at which near-gravity material accumulated within the cyclone when treating diamondiferous ore was much smaller than that for the lead-zinc ore, and it is believed that it was for this reason that the \( z \) parameter shown in Equation 32 for the Argyle data was small.

Cyclone operation with as low a medium viscosity as possible will reduce the magnitude of \( k \) and increase cyclone efficiency. Unfortunately, low viscosity operation contributes to high density differentials, which under certain circumstances will cause inefficiencies due to internal crowding and particle interference. It was concluded that in practice an optimum condition must exist that is determined by the quantity of near gravity
material in the feed ore, and that ores with very little near-gravity ore can therefore tolerate large density differentials.

8. SUMMARY, CONCLUSIONS AND FUTURE WORK

This project has proceeded a long way towards the goal of a general, quantitative DM cyclone model which can be used in simulation for process design and optimisation. The pivot phenomenon has been established as real, and it has been incorporated into a model structure which has been shown to describe well the data sets generated in this programme.

The development of general regression equations to predict the model parameters has suffered from the small database currently available. However, within this constraint the predictions for particular environments are good, and show promise for an enlargement of their range of validity. These models have shown quantitatively how important system variables such as medium viscosity, ore feedrate, feed density distribution and cyclone diameter affect the prevailing separation. Taken together, they provide a valuable insight into the factors which are important in determining cyclone performance.

A summary of the numerical models and suggested computational routes for simulation is given at the end of the two sections describing the pilot scale and industrial modelling (Sections 4.1 and 4.2).

As they stand, the application of the models to real simulation problems has yet to be tested, and clearly a considerable degree of specialist interpretation will be necessary in applying them to particular problems outside the experimental environment in which they were developed.

In order to build on what has been achieved, three lines of enquiry must be pursued:

1. The present models must be tested in simulation. This will be possible when JK Tech completes the development of the Dense Medium Module of the Mineral Processing Simulator, JKSimMet, early in 1990. This module will incorporate elements of the cyclone models described in this chapter.

2. The model structure must be validated in a new site. Surveys of Hamersley Iron’s Tom Price DM cyclone plant are planned for to satisfy this objective.
3. The general database must be extended. This will be done as opportunities present themselves. However, two aspects will be considered in the short term:

- Incorporation of the considerable volume of coal data available at the JKMRC.
- Utilisation of a new method of inferring density distributions from limited sample data. This method, currently being evaluated at the JKMRC, has the potential to ease significantly the problems associated with performing heavy liquids analysis on ore samples, and thus to increase the rate of acquisition of appropriate data.

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NOMENCLATURE

(All units are SI, except for particle size which is in millimetres)

- \( \alpha \) efficiency curve parameter
- \( D_c \) cyclone diameter
- \( D_u \) cyclone apex diameter
- \( D_o \) cyclone vortex finder diameter
- \( d \) particle size - size \( i \) indicated by subscript \( i \)
- \( d_{50c} \) corrected classification cut-size
- \( \Delta \rho \) density differential \( (\rho_l - \rho_0) \)
- \( E_p \) ecart probable
- \( \mu \) equivalent apparent Newtonian viscosity - subscripts (l) liquid, (p) pulp
ndf number of degrees of freedom
NDP number of data points
$\rho_p$ pivot density
$\rho_{50}$ separation density
$\rho$ density - subscripts (l) liquid, (s) solid, (m) medium, (f) feed medium, (u) underflow medium, (o) overflow medium
Q cyclone feed volumetric flow rate
r radius
Re cyclone Reynolds number $= \rho_f V_i D_c / \mu$
Rm pulp split to underflow
$\sigma$ standard deviation
V Velocity - subscript i indicates inlet velocity
$V_f$ volume fraction of solids in feed medium
$V_{FR_p}$ pivot volume fraction ratio equal to $V_p / V_f$
$V_{FR_u}$ volume fraction ratio for the underflow pulp
Vmo volumetric medium pulp to ore ratio
$V_p$ medium solids volume fraction equivalent to pivot density
$Y_p$ pivot partition number
z $E_p$ crowding parameter

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