3 LITERATURE SURVEY AND THEORY

3.1 Ore dressing simulators

(In this work, only steady-state simulation will be considered.)

The objectives of simulation on the plant have been outlined above. Ford (16), and Ford & King (17) present a general outline of the uses of simulation in the metallurgical industries. King (33) and Laguitton (35) discuss the use of the computer in solving metallurgical problems. Bloise (1) considers only modelling in ore treatment, outlining its objectives and limitations.

Steady-state simulation is a process of solving a system of non-linear algebraic equations which represent the mass balance of a process system.

Their solution can be done in 3 ways

- sequential modular
- equation oriented
- two-tier

Most industrial simulators use the first approach (11), using a library of subroutines (modules) which express the unit operation output as a function of the input and unit parameters according to a unit model. Each unit model is called in order of appearance in the flowsheet or in an order in recycle loops determined by partitioning and tearing the recycle, estimating unknown parameters and using convergence techniques to balance the loop. This will be discussed later.

Equation oriented methods use the model equations to establish a system of equations for the process which are then solved simultaneously, if indeed a unique solution exists. This method is usually used for unit modelling only, as it is too cumbersome for modelling an entire plant, but can be used for dynamic simulation. This is a very flexible method of simulation.

Two-tier algorithms can use a sequential modular approach to the flowsheet, while incorporating both simple linear unit models which are easy to solve and more rigorous models which require equation

solving techniques similar to those of the equation oriented methods. Therefore, after initial simulations with simple models, a more rigorous simulation can be performed with advanced models. A similar method is the simultaneous modular method, solving the flowsheet by solving simultaneously a system of linear equations of the simple unit models for the stream variables. This can be seen as a convergence technique, the final simulation being done by more rigorous methods. This method is of particular use when design by iterated simulation is used. Simple models can be used to save computer time during convergence towards the optimum design, whereafter the advanced models can be used for refinement and final equipment specification.

The sequential modular and two-tier approaches are mathematically more robust than the equation oriented approach, and can incorporate any number of models. However this advantage is gained at the expense of additional computer time for design and optimisation problems, where repeated simulation is used to converge to an optimum.

For a general purpose simulator, it is important to choose a method which will provide an acceptable solution for the given study. It also helps the user if models are always written in the input to output form, since the simulation problem can use many existing models and the problem is always well defined. For our purposes, a sequential modular type simulator was thus thought best.

The sequential modular approach can be thought of as consisting of two parts, the flowsheeting software (executive) and the unit model library. Flowsheeting may be defined as the use of computer aids to perform steady-state heat and mass balancing, sizing and costing calculations for a process, whereas the unit model calculates the transformation brought about within the unit.

Chemical process simulators were the first to use this approach. Examples of such simulators are Chess, Aspen and Flowtran, (45,46).

In ore dressing processes energy balances are usually not required, simplifying the calculational procedures considerably. This simplification is counteracted by the fact that a very large number of species (particles of different sizes having different characteristics) are present and must be taken into account. Stream

description must be adequate for this purpose.

Work has been done in extending chemical process simulators to meet the needs of metallurgical process simulators. From Aspen was developed Aspen Plus (46), which can only be implemented on a mainframe computer, but which incorporates advanced stream data structures and precalculation algorithms. Flowtran has been only slightly extended. Flexmet (45) on the other hand was written for metallurgical evaluation but has limited solid phase description.

Rexnord's Computer Analysis Program (28) is a simulator designed for use on crushing and screening circuits where Rexnord's equipment is used. It is not commercially available.

The Julius Kruttschnitt Mineral Research Centre simulator (23) is one written specifically for ore dressing, and again is limited to use on a mainframe. Modsim (16,17,31,32), the original simulator on which work was done, follows a very similar concept, and is available in both mainframe and microcomputer versions. A variation of this simulator Utah-Modsim (22) is available only at the University of Utah. The mainframe version is written completely in Fortran, whereas the microcomputer version uses a Pascal graphics portion, namely that used in Microsim (7,8,34,50,51). Microsim is a considerable extension of Modsim, incorporating more advanced data structures capable of handling hydrometallurgical operations, written entirely in Pascal and is file oriented.

Because of the existing characteristics of Microsim and its expandability to further stream types, it was decided to continue work on Microsim, rather than Modsim. Microsim Version 3.0 also provides for optimisation using the simplex method to repeat simulation. Microsim is only available on microcomputer and as such is eminently suitable for a mining environment. A critism of Microsim is that its error handling is not yet adequate for users without a thorough background in its use and its models.

It is useful to mention that simulators are available for specific crushing plant situations, for example, those of Whiten (56) and Pederson and Gurun (41). Karra (25) uses limited simulation to calculate circulating loads in closed circuit crushing. Much work has been done on flotation and grinding, but will not be considered here.

A coal plant simulator written by the US Department of Energy is available (19,20). Anglo-Alpha's Apollo (21) uses a linear programming optimisation for crushing aggregates. These simulators are not relevant in this work, and hence will not be considered here.

3.2 Microsim

3.2.1 Introduction

Microsim is a sequential modular metallurgical process simulator operating on an IBM-compatible microcomputer with a minimum configuration of two floppy disk drives and 256kB memory. The amount of memory restricts the size of the simulation which can be carried out. The computer system used in this work is listed in Appendix 1.

Written in Pascal Version 3, using dynamic storage and possible co-processor support (8087 or 80287) for faster calculation, Microsim is menu driven with data input in form-filling mode and flowsheet input in drawing mode using a graphical interface.

Microsim is structured into four phases:

(1) flowheet input
(2) ordering of the flowheet
(3) data entry and calculation (whether simulation, optimisation or design)
(4) tabular or graphical output of results

These phases are described below, after some theory concerning computational simulation.

Ore dressing plants have process streams largely composed of solids and/or water. Ford (16) in Modsim characterized the solid phase by a three-dimensional (3-D) description viz. size (D), grade (G), and a further characteristic (S),which would be of use with models exploiting particulate mechanics, e.g. floatability or shape. Grade represents the percentage of desired mineral in the particulate material. Note that a discrete number of D, G and S classes are used. This can be described computationally by a 3-D array which is both easy to understand and program.

Hydrometallurgical operations are not part of this plant, but are used elsewhere. For the purpose of this work a 3-D data structure may be assumed, since there are utility routines which will make the actual plex data structure transparent to the user. Cilliers (7) provides full details of the data structure, which can be expanded to an apparent 5-D structure for use with advanced hydrometallurgical

operations. As mentioned previously, for the plant, a 1-D data structure will suffice for work on the first, second and fourth sub-plants.

3.2.2 The Particulate State

Ore dressing unit models exploit particulate mechanics, hence the particulate state must be well defined. Unlike chemical processing, in ore dressing the particulate material consists of a very large number of species (particles), each with different properties.

The mathematical description of these particles is based on probability theory, using a distribution function. The most common distribution is the particle size distribution function, F(dp). The particle size definition used throughout is the smallest square wire mesh that permits the passage of a particle under gravity with prolonged shaking.

This distribution cannot be used in its continuous form for modelling purposes (or laboratory work) and hence needs to be discretized. The resulting function is f(dp)(delta.p), where (delta.p) is the size class width and usually varies as size classes are expressed as a geometric series with a power-of-2 factor.

Within each size class the properties of all particles are assumed constant and equal to the average, expressed at the geometric mean particle size in the class. The smaller the size class the better the approximation, but the more computational effort required. The two extreme size classes use a series approximation to the average size, as an average size cannot be defined.

Microsim can use up to 40 size classes and the well-known size distributions are intrinsic functions. These include the Rosin-Rammler, Schuman, Broadbent-Callcott, Gaudin-Melloy and Harris distributions as defined in (8).

The distribution of particles according to grade is likewise expressed in terms of grade classes of finite size with average mineral composition. Up to 10 minerals can be incorporated into a Microsim simulation, but 2 minerals are most commonly used. Microsim automatically specifies a pure (completely liberated) class for each

mineral specified whereafter additional classes are user-specified.

Liberation of minerals into grade classes can be adequately modelled and incorporated into the simulation. Because of the configuration of the plant , grade classes will only be used in sub-plant 2, using observed distribution of ore. It is assumed that liberation does not vary markedly with operation of sub-plant 1, but rather with differing run-of-mine characteristics, which require new simulations.

The physical property (S) values are finally specified for each of the classes defined. If the specific gravity is the characteristic property, the specific gravity of the pure minerals can be specified (if indeed they are known) and Microsim will calculate the S-property for each class. Otherwise, the user must input the appropriate value for each defined class.

Wet streams are catered for by adding the water rate as a percentage and giving the tonnage of the solid phase, or as a water flowrate in tons per hour.

Once the solid phase has been defined for a flowsheet, the solid phase class description must be maintained for all solid (sub)-streams in the flowsheet.

3.2.3 Unit Models

The Microsim library contains models for most ore dressing and hydrometallurgical unit processes. These models all take input stream data to the unit, and calculate the output stream values from the input data, unit parameters and model theory.

The only models of application on the plant are cone crusher models, vibrating screen, drum separation and cyclone separation models. The plant uses other units but these are not in the main metallurgical flowsheet, and hence will not be considered here.

For crushers the following models are available:

- Whiten
- Nordberg Gyratory
- Nordberg Symons
- Shorthead

For screens the following models are available:

Ideal
Karra
Rogers

For drum and cyclone separation only one model each is available.

Mixers will be used as a separate unit on the simulation flowsheet to conform to the simulator's requirement that only one process stream is input to a unit, a requirement which has important mathematical consequences in simplifying calculational procedures.

Furthermore, the plant metallurgical flowsheet contains gyradisc crushers and dewatering screens which are not contained in the Microsim unit library.

Existing and new models were investigated for their relevance in the flowsheet of the plant, as documented in a later section.

New models can be incorporated into Microsim by following the rules (8) for the input data structure and the specification that unit models be written as a transformation of an input stream to output stream(s) through unit and material parameters.

3.2.4 Precalculation, Simulation and Optimisation

A flowsheet is first entered into Microsim using the editor, whereafter precalculation and simulation are performed.

Precalculation is done in the sequential modular method by partitioning, tearing and ordering the flowsheet, so that a precedence order of subroutine (unit model) execution is established for sequential simulation.

The flowsheet is partitioned by breaking it into groups of units called unit maximal cyclical loops so that the information in the simulation only flows forward. These groups can contain recycle streams, i.e. streams with unquantified variables the first time a unit operation is executed.

Recycle loops must be 'torn' open so that the process is no longer

cyclical. Unknown variables are initially assumed using default values and an iterative technique is used to obtain convergence of the unknown variables to within a specified tolerance to quantify these recycle variables.

Tear streams can occur in many combinations. Optimal tear streams are determined in the precalculation phase for best convergence of the overall flowsheet.

Once all the tear streams have been determined a calculational order within the unit maximal cyclical loop is apparent and the loop can be solved sequentially.

The final calculational order is hence obtained by combining the order of all the loops, whereafter simulation takes place.

In Microsim the partitioning is done according to Tarjan's algorithm and determination of the set of torn streams is done by a modified Lee and Rudd algorithm as described by Cilliers (7). Convergence methods available in Microsim are direct substitution (which is slow) and the bounded Wegstein method (an accelerated convergence method), which Ford (16) discussed and compared.

Simulation can now proceed sequentially according to unit models. Note that convergence is not guaranteed, especially if models are complex or defaults far from solution. For this reason it is best to break flowsheets into smaller units, where possible.

If the optimisation (or design) option of Microsim is chosen, the user specifies what is to be optimised (or what unit parameters are to be designed). Microsim then asks for initial guesses at any unknown parameters. Now the simulation calculation proceeds as above, and the results compared with the optimisation target (or design specification). A simplex optimisation (5) routine within Microsim then improves on the initial guesses and repeats the simulation with these. The simplex method itself does not diverge, but can occasionally terminate prematurely, leading to erroneous results.

3.2.5 Using Microsim

It is evident from the above that Microsim is used in three phases:

- flowsheet graphics editing
- ordering the flowsheet after partitioning and tearing
- performing simulation or optimisation calculations.

Information is passed between sections of the package using data files.

The three main programs within the package corresponding to the abovementioned phases are:

- FLWSHEET.PAS
- ORDER.EXE
- OVERLAY.PAS, renamed SIMULATE.COM when compiled.

Flowsheets are input by drawing the process units using icons on the screen, with each icon corresponding to a metallurgical process unit. The units are then joined by streams corresponding to the flow of material on the plant. Certain rules must be adhered to when inputting flowsheets, otherwise an error message is given to the user. Editing of the flowsheet and labelling can also be done.

The flowsheeting software must be modified if new icons (new units) are to be added to Microsim, or if different graphics drivers are used.

Changes required for new graphics drivers are different extensions for include files and ensuring that the correct driver statements are commented out in the file TYPEDEF.PAS.

Adding new icons requires:

- updating certain CONSTANT statements
- adding code to draw the icon
- adding code describing latch points for feed and products
- adding case statements to draw the icon by striking a key.

Data files are created by this program for plotting purposes as well as for transferring information to further sections of the program.

The ordering routine receives the stream connection matrix from the

flowsheet editor and from this decomposes it into cyclic nets and outputs the order of unit execution and the tear streams, all in appropriate data files. As this is a formal algorithm it need not be modified and is supplied in executable form only.

The main program, in the form of SIMULATE.COM, calls the unit models and performs each unit calculation sequentially.

The pertinent information for the system is contained in three sections viz. system data, unit data and stream data sets.

The system data set defines the size of the problem (i.e. number of size and grade classes, etc.). Utility routines enable the data to be represented by an apparently 5-D data structure which can accommodate any combination of solid, lixiviant and carbon process streams.

The unit data set consists of that data necessary for the each unit simulation and includes model type and model parameters. For each model type there are default parameters.

Streams data define the contents of each stream in the flowsheet, using a powerful user created Pascal data structure. This structure again appears five-dimensional to the user as utility procedures manipulate the pointers of the actual structure. The five-dimensional structure represents the distributed properties of the solids.

The data files containing the system, unit and stream data are created for each flowsheet and have extensions .SYS, .UNT and .STM respectively. The contents of these files are input from the screen in form-filling mode, with default values obtained from the database.

Models can be added to the system to extend the range of models available.

Adding new models requires:

updating constants in TYPEDEF.PAS
updating case statements to call the new unit
recompiling the main program and
updating the model database.

For more advanced modelling of hydrometallurgical processes, new data structures may need to be added. This does not apply to ore-dressing simulation and will not be included.

After simulation or optimisation calculations are done, results are obtainable on screen or on disk in the form of mass balance tables, size distribution tables or plots, and unit partition curves. Design reports are available for some units in the report file.

All files for a given flowsheet are saved under the flowsheet name, with appropriate extensions, so repeat simulation is straightforward. Microsim has an inbuilt data editing facility, so that the user can rerun flowsheets with different stream and unit data at will. Some DOS utilities are also provided.

Although robust, Microsim is limited to steady-state simulation, and cannot guarantee convergence or optimisation in every case. Flowsheet size is limited by disk space. Because Microsim considers units in parallel as a single unit, it is left to the user to check that the capacities of units are not exceeded. Nevertheless, it remains a powerful simulator.

3.3 Crushing

3.3.1 Introduction

On the plant crushing is the only comminution operation. The crushers are all of the form of gyratory cone crushers viz.

- primary gyratory crushers
- secondary and tertiary Symons cone crushers
- quaternary shorthead cone crushers
- quaternary gyradisc crushers

The various types of crusher are shown in figures 8a to 8c.

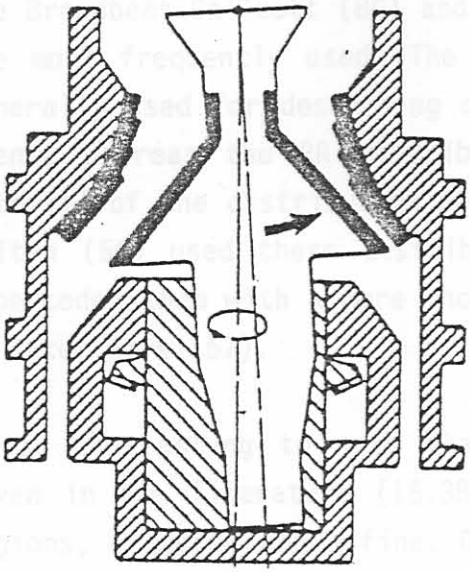
To date crushing has not been much modelled as crushing has been considered as a conditioning prior to grinding. Beyond empirical modelling by manufacturers, only Whiten's work (56,57) on cone crushers and its extension to shorthead crushers by Karra (27) incorporates a theoretical treatment.

Material flow in a cone crusher is closer to plug flow than that in a grinding mill, where flow mixing is considerable. Breakage events in a crusher are time discontinuous, as compared with the continuous breakage in a grinding applications. Crushing must thus be considered in a different light.

An improved approximation to plug flow in a crusher is that which allows for classification of fine material through the bigger material trapped in the crusher cavity, with comminution affecting only those trapped particles, which thereafter are classified, etc. This type of material flow is the essence of Whiten's model.

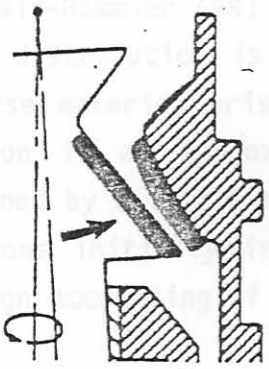
The most popular method of comminution modelling was to obtain a best fit curve through a plot of output size distribution from the crusher. This curve is usually only thought to be a function of the crusher closed side setting (CSS) and the impact work index (IWI) of the material. The manufacturers' information can be thought of as models of this type.

There is disagreement among theoreticians as to whether the energy-breakage relationship can be expressed by the laws of Kick, Rittinger or Bond. Robert (47) discusses these laws, and Ford (16) discounts their use for simulation as they do not take into account material



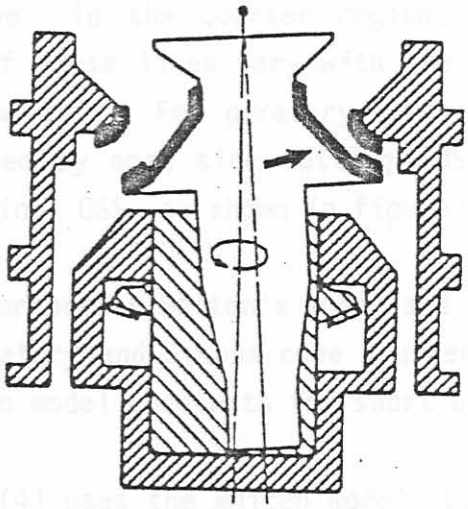
Cone

Fig 8a Symons cone crusher



Short Head

Fig 8b Shorthead cone crusher



Gyradisc

Fig 8c Gyradisc crusher

flow in the crusher. For this reason some models do not attempt to incorporate particle breakage mechanics, preferring to predict the output size distribution caused by the total breakage events by using empirical distributions.

The Broadbent-Callcott (BC) and Rosin-Rammler (RR) distributions are the most frequently used. The BC distribution is empirical and is generally used for describing coarse material arising from breakage events whereas the RR distribution is an approximation for fine material of the distribution obtained by Griffith crack theory (29). Whiten (56) used these distributions initially in his models, but superceded them with a more thorough accounting of particle breakage in later work (57).

It is interesting to note that crusher output size distributions given in the literature (15,38,39,57) indicate very distinctly two regions, a coarse and a fine. On a log-log or RR plot these curves approach straight lines to varying degrees. For secondary and smaller crushers, output size distributions from Nordberg (38) plotted on RR scales can be well approximated by two straight lines, with the steeper slope in the coarser region, as shown in figure 9. The intercepts of these lines vary with the CSS of the crusher and the IWI of the material. For gyratory (primary) crushers the intercepts are determined by open side setting (OSS), IWI and percentage of product passing OSS, as shown in figure 10.

Microsim incorporates Whiten's model and the empirical models for the Nordberg gyratory and Symons cone crushers and Karra's modifications of the Whiten model constants for short head Symons cone crushers.

Utah-Modsim (4) uses the Whiten model, but Modsim (16) uses the time discontinuous statistical equation that is the precursor to the full Whiten model, relying on the user to use any number of 'crushers' (as represented by the equation) and/or classifiers in series to model an industrial crusher. This does provide more flexibility but renders the simulator cumbersome to the uninitiated user.

3.3.2 Whiten's model

Whiten's model (56,57) incorporates a classification (c) and a breakage (P) function in recycle as shown in figure 11.

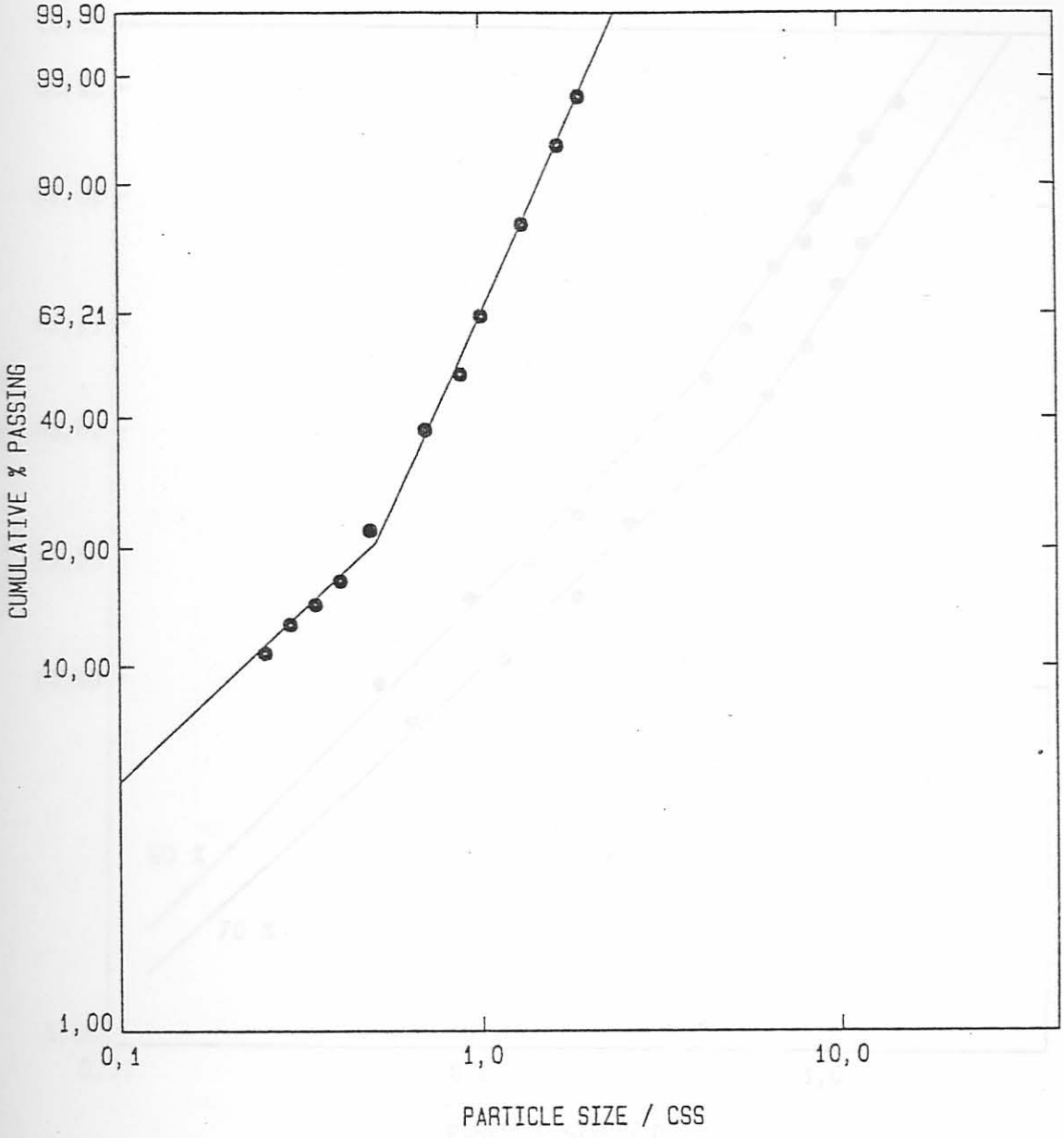


Fig 9 Rosin-Rammler plot for output from a Symons cone crusher

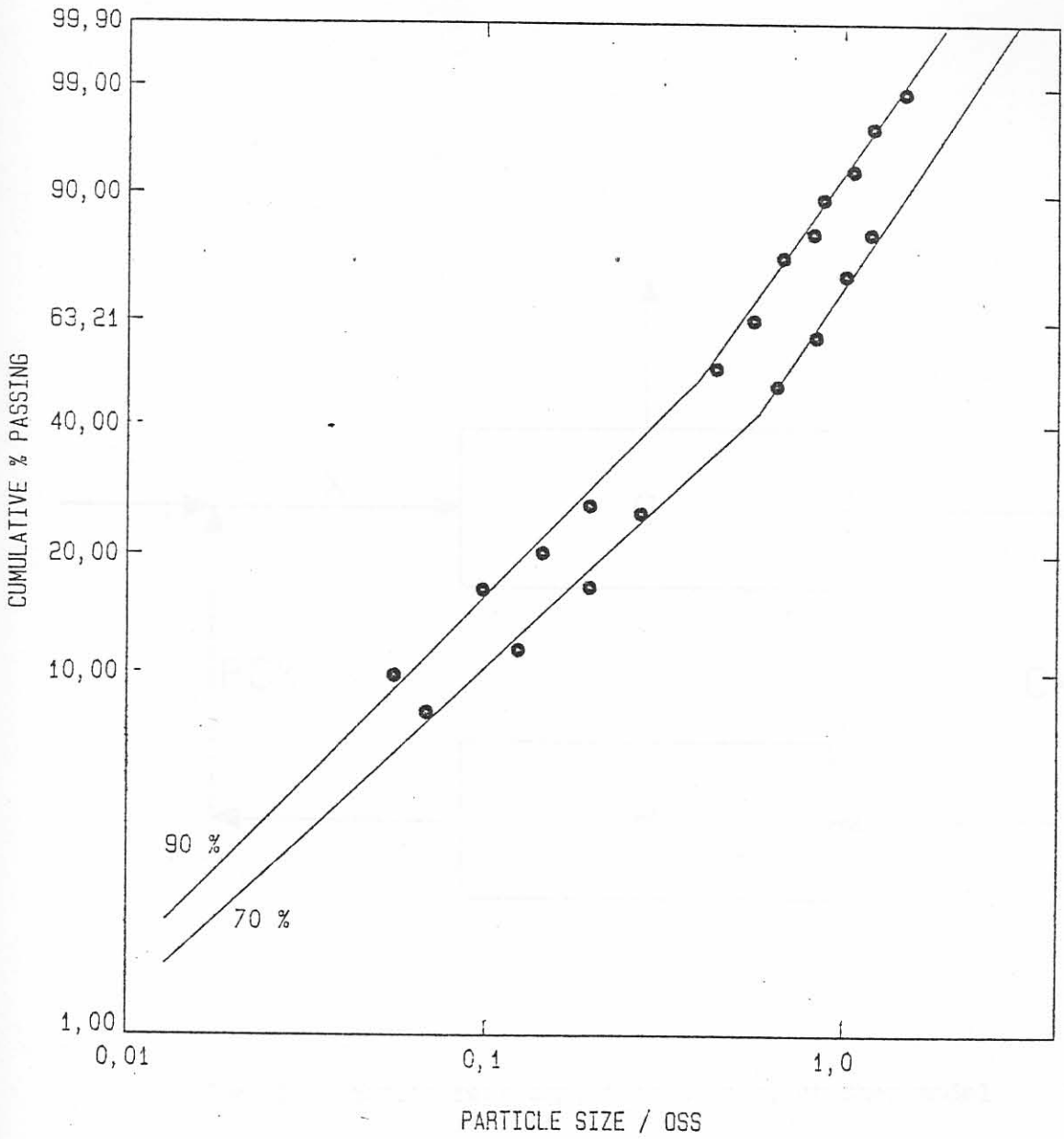


Fig 10 Rosin-Rammler plot for output from a gyratory crusher

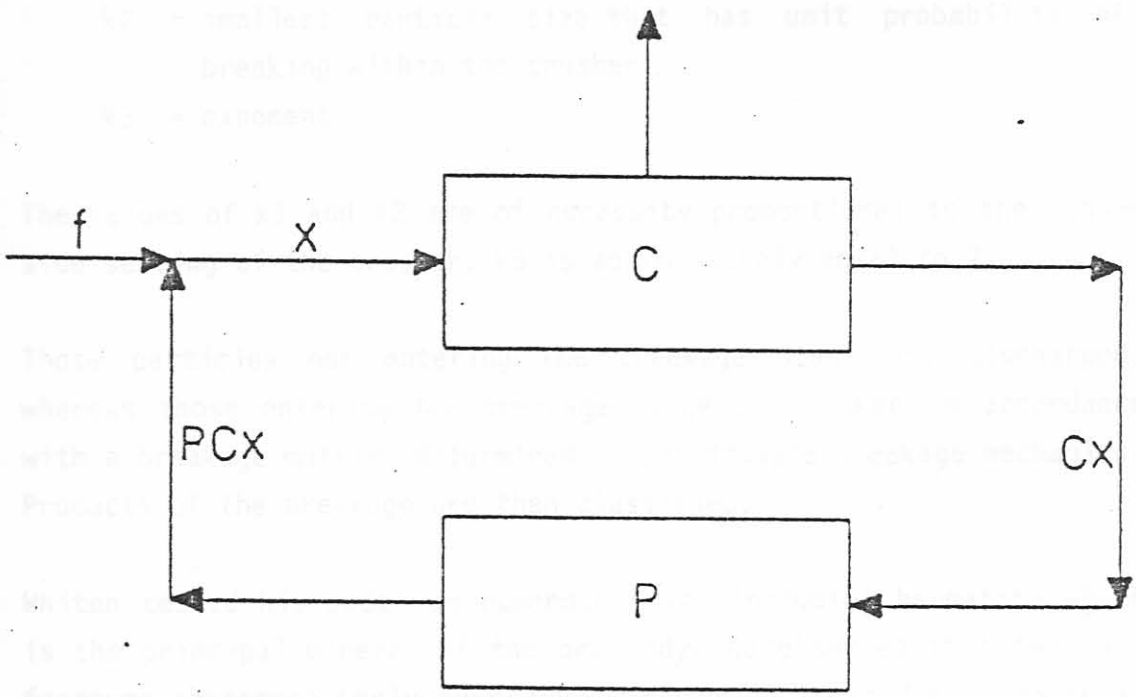


Fig 11 Symbolic representation of cone crusher model

Particles entering a crusher are first subject to classification. This implies that the probability of a particle entering the breakage stage is a function of particle size, x. The fractional classification function, c, can be written as:

$$c = 1-((x-k2)/(k1-k2))^{k3}$$

where

k1 = maximum size of particle that passes through the crusher without breaking

k2 = smallest particle size that has unit probability of breaking within the crusher

k3 = exponent

The values of k1 and k2 are of necessity proportional to the closed side setting of the crusher. k3 is approximately equal to 2.

Those particles not entering the breakage stage are discharged, whereas those entering the breakage stage are broken in accordance with a breakage matrix, determined by particulate breakage mechanics. Products of the breakage are then classified.

Whiten tested his model on numerous ores, including haematite which is the principal mineral of the ore body. He observed that the same fracture phenomena apply over a wide range of ore bodies. The model was then established to include parameters which will accommodate various ores' propensity to breakage according to the fracture phenomena observed, various operating conditions and various machine types.

Two major fracture modes are identified by Whiten viz. fracture due to tensile stress producing two or three large pieces and fracture due to compressive stress producing characteristic fines. The final size distribution depends on the proportion of a particle size class that breaks under tension and the size distribution resulting from breakage from both fracture mechanisms.

Using particulate mechanics, the total fraction, P, of size less than x produced by breakage of particles of size y was found to be approximately

$$P = (1-K)(x/y)^n + K(x/y)^m$$

where

K = proportion of fines produced during breakage events

n = exponent determining slope of distribution formed by tensile fracture

m = exponent determining slope of distribution formed by compressive failure

On a log-log plot of output size distribution the values of m, n and K can be found approximately. The slopes of the fine and coarse portions yield m and n and the extrapolation of the linear portion of the fine region of the distribution to the original particle size (i.e. x = y) yields K.

From mechanical considerations for various ores, K has an upper bound of 0,2 and n was found to have an average value of approximately 3. The value of m could vary between 0,3 and 1,05. In fact, m was found to fall between 0,4 and 0,65 for ores tested.

Results of individual fracture tests on various ores, including haematite, in the size range 63 to 13mm, for one, two and five major fractures showed similar size distributions to those of the output of an industrial crusher with the difference that more fines are produced in cone crushers. The gradient of the fine portion of the distribution, m, was shown to be independent of the number of fractures and of particle size of the original material. K increases with the number of breakage events and n decreases. For one breakage event, n increases with particle size of original material.

The increase in K with each successive breakage event indicates that each breakage event is indeed a repetition of the same breakage mechanisms as postulated, hence validating the use of a repetitive breakage and classification model.

For secondary and tertiary crushers it was found that closed side setting (CSS) has the most significant effect on product size distribution. When the CSS decreases the product becomes finer over the entire distribution, the top size decreases and the proportion of fines increases, but the gradients of the product size distribution do not vary significantly.

For primary crushers, only the top size was found to decrease with decreasing CSS.

The feed rate affects only the proportion of fines produced, increasing K slightly for increasing feed rate. This dependence on feed rate was found to be much less than the dependence of K on closed side setting. The top size of the product distribution together with m and n did not vary with the feed rate.

Whiten found that for haematite the input feed size distribution had no significant effect on the product size distribution.

The value of K used must correspond to both the feed rate and the closed side setting of the crusher.

3.3.3 Model Comparison

From the work of Whiten it can be seen that the empirical models which predict that output size distribution varies with CSS and ore type and not with feed size distribution are valid. However, the empirical models studied do not cater for the effect of varying feed rate on the product size distribution, and hence limit their validity to 'normal operating conditions'.

3.3.4 Gyradisc crushers

No theoretical development of models for a gyradisc crusher could be found in the literature. Nordberg are the only manufacturers of gyradisc crushers and they provided the design information for these crushers (38, 39).

The crushing mechanism in a gyradisc crusher is largely interparticle comminution. The configuration of the crusher is shown in figure 8c. The angle of the lower liners is less than the natural angle of repose of the material, hence a classification mechanism cannot be valid for a gyradisc. Discharge is effected by rotation and the introduction of new feed. It has been observed that increasing the CSS will coarsen the product, though no indication of the functional dependence of this effect could be found.

It was evident that an empirical model would have to be developed.

3.4 Screening

3.4.1 Introduction

The screening process is most vital to the operation of the plant, as it is through screening that the final products are recovered and financial penalties are incurred for products beyond specification sold on the export market.

Numerous screening models have been developed recently, using diverse approaches. Kelly and Spottiswood (29) report that no satisfactory theory on screening has yet been formulated.

The prediction of screening efficiency is one of the most crucial factors in screen modelling. The definition of screening efficiency used in this work is the percentage of true undersize in the feed which reports to the underflow product. Leonard (36) discusses seven definitions of screening efficiency, but the definition used here is chosen to conform with the definition used for existing models in Microsim and that used on plant.

3.4.2 Empirical models

Empirical screening models are usually supplied by the manufacturers of screens and coincide with the information used in screen design. These largely estimate only screening efficiency and do not give an indication of distribution of undersize in the overflow. Practice has shown that these models frequently overestimate the screening area required and hence are conservative models.

Screening performance, according to Kelly and Spottiswood (29), depends on the following:

- relative size of particle and aperture
- screen movement
- screen surface:
  - % open area
  - aperture shape
  - aperture and wire diameter
  - size of screen surface
  - angle of inclination
  - deck location in multideck screening

bed depth
moisture content.

Many of these factors are built into the empirical models and modify the overall screening efficiency.

To quantify the distribution of undersize in the overflow, it is best to represent the screening process by a partition curve similar to that used in determining cyclone separation. Partridge (40) supports the use of the partition curve to describe screening performance.

The use of partition curves in screening is gaining popularity and has been used in the following work:

Brereton (2), Brereton & Dymott (3)
Karra (27)
Rogers (48)
King (30)
Ferrara and Preti (12), Ferrara, Preti & Schena (13,14)
Batterham et al., Molerus & Hoffman, quoted in Rogers (48)

Figure 12 shows a generalized partition curve for ideal and real screening. The determination of the mathematical form of the real curve has been done in various ways.

Brereton (2) assumes that the partition coefficients for each particle size representing the probability of a particle passing through a screen follows a normal distribution, and hence derives an anamorphosed partition curve which can be characterized by two parameters. These two parameters are the separation size, d50, and the 'Ecarte probable moyen' or Epm. He also describes a procedure to obtain these parameters experimentally. Brereton believes that this distribution is valid in the case of no interparticulate interaction during the screening process. This is obviously not strictly true in industrial screening where high feed rates are maintained, but results show that it is an accurate approximation.

The Poisson distribution predicts the probability of a time interval event occurring within a time aperture. King (30) equates the cross-sectional area of screen apertures and the cross-sectional area of particles with time interval events and tome apertures and then derives an equation for predicting 'overs%' by integration. The

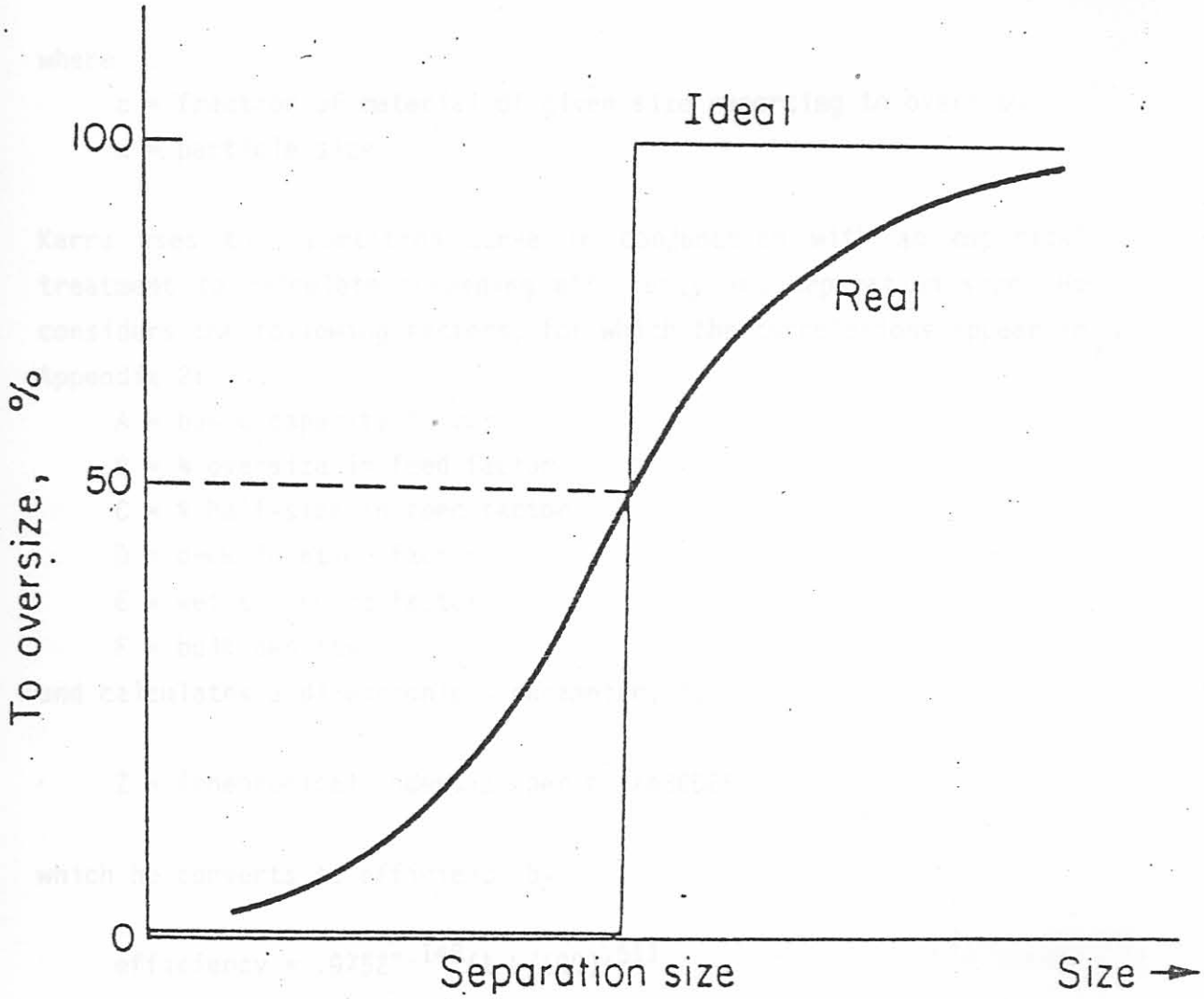


Fig 12 Partition curve

differential form of this equation would then represent a partition curve.

A determininstic equation may be used to describe the partition curve. Karra (28), measuring screening performance of industrial scale applications screening -20/+2mm stone, uses the form

$$c = 1-\exp(-0,693(x/d50)^{5,846})$$

where

c = fraction of material of given size reporting to overflow

x = particle size

Karra uses this partition curve in conjunction with an empirical treatment to calculate screening efficiency and separation size. He considers the following factors, for which the correlations appear in Appendix 2:

A = basic capacity factor

B = % oversize in feed factor

C = % half-size in feed factor

D = deck location factor

E = wet screening factor

F = bulk density

and calculates a dimensionless parameter, Z, as

$$Z = (\text{theoretical undersize per } m^2)/ABCDEF$$

which he converts to efficiency by

$$\text{efficiency} = .975Z^{-.148}(1-L/100)^{.511}$$

where

L = % near-mesh in feed.

The separation size is then found from the correlation

d50 = efficiency(throughfall aperture),

whence the partition coefficients are calculated.

This form of equation for the partition curve is recommended by Ford (16) and is identical to that used by Petno and Tompos (43) who specify a range of values for the index which includes the value found by Karra. This index is called the sharpness of separation.

Rogers (48), whose work was in wet screening, uses an equation of form

$$c = 1/(1+\exp(\text{alpha}(1- (x/d50)^3)))$$

where

c = fraction of material of size x reporting to overflow

alpha = sharpness of separation.

Rogers uses a best-fit method to calculate d50 and alpha from experimental data and does not indicate how these parameters vary with screening conditions.

In modelling work using a partition curve, care must be taken that the d100 size is less than the aperture as this places a limit on separation.

Many equations exist which represent the probability of passage of a particle of given size, most notably that of Gaudin (18), which has been used as a precursor for numerous screen modelling attempts. Calanog and Geiger (6) refer to his work and their extension of it to non-spherical particles and present a screening model for cost of a vibrating screen.

Whiten (56) and Walter and Whiten (55) document their work in screen simulation which improves on Gaudin's work.

3.4.3 Kinetic models

Other workers have followed a kinetic approach to screening. In figure 13 the screening process can be seen to consist of three regions. Kelly and Spottiswood (29) and Partridge (40) both describe the screening process in this manner. The initial region is that where stratification takes place, the second where crowded screening (defined by interparticle interaction) occurs, and the third region is where separate screening takes place.

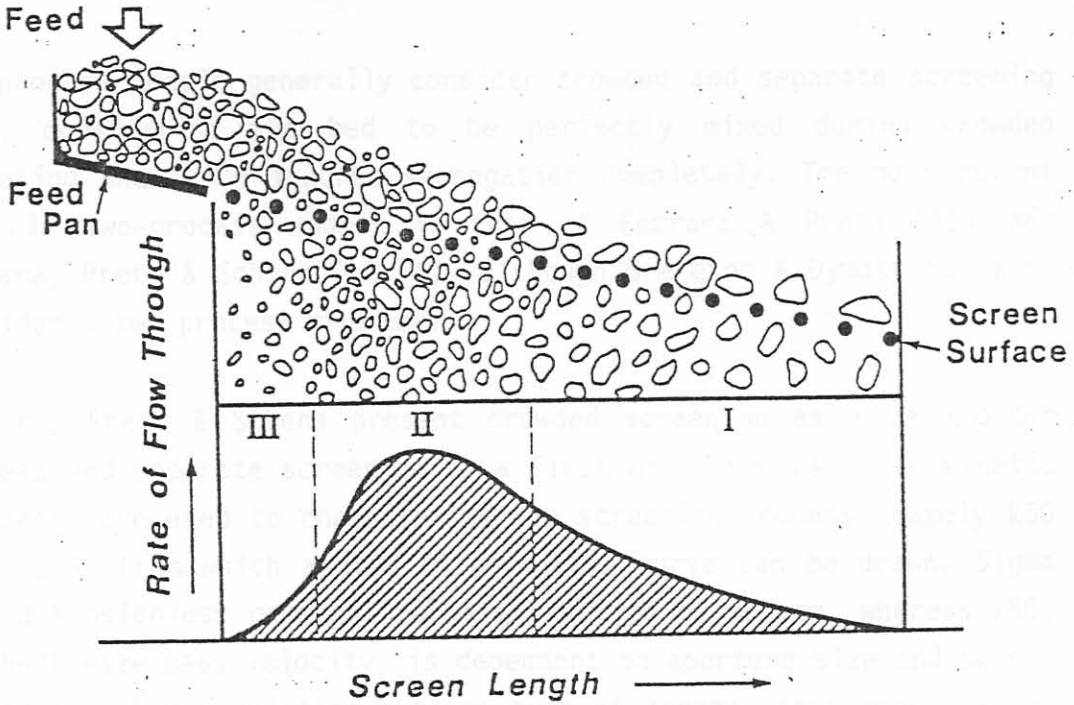


Fig 13 The three major regions occurring along a screening surface

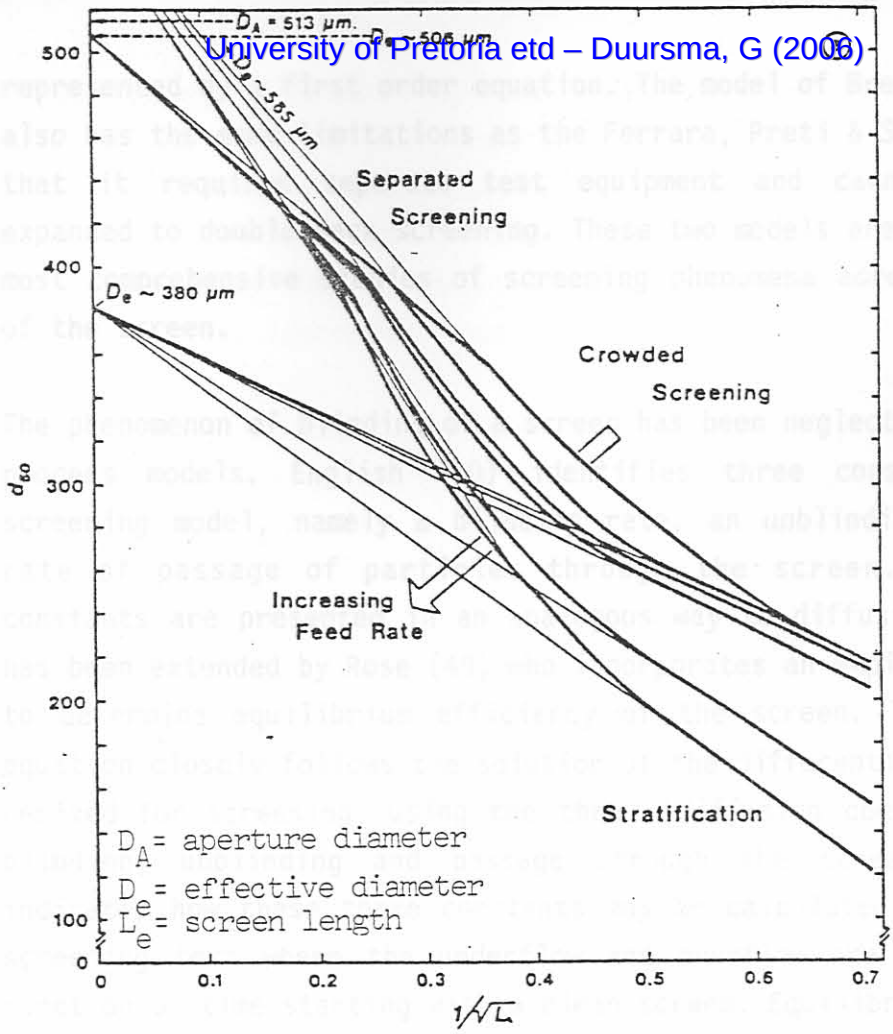
Despite the identification of three screening regions, much work has been done in which screening is considered as one process. Kelly and Spottiswood (29) document some of these one-process models and indicate the work of Miwa which identifies an equation relating the separation size (d50) to the inverse of root length. From this relation the screen index and the effective aperture can be calculated. The screen index is an indication of the screen movement, inclination and bed characteristics.

Two-process models generally consider crowded and separate screening only, considering the bed to be perfectly mixed during crowded screening and hence ignores segregation completely. The most recent work in two-process models is that of Ferrara & Preti (12) and Ferrara, Preti & Schena (13,14), although Brereton & Dymott (3) also consider a two process treatment.

Ferrara, Preti & Schena present crowded screening as a zero order process and separate screening as a first order process. Two kinetic constants are used to characterize the screening process, namely k50 and sigma, from which a type of partition curve can be drawn. Sigma is a dimensionless constant for a given type of screen, whereas k50, the half-size mass velocity, is dependent on aperture size and screen properties. For simulating a given type of screen, this model can be thought of as a one parameter model.

These constants cannot be derived and must be obtained experimentally using a test screen where the underflow can be collected along the length of the screen.

The Ferrara, Preti & Schena model requires separate test equipment and because it cannot easily be extended to double deck screens, where feed to the second deck is across the length of the screen, this model was not considered for development. Furthermore, the assumption that segregation can be ignored is not entirely valid. Kelly and Spottiswood (29) mention that screening area requirements can be halved if segregation is allowed to occur. That segregation occurs can be seen from the results of Brereton & Dymott (3), as plotted in Kelly & Spottiswood (29), where three distinct regions can be identified for most flowrates across the screen. From these plots, shown in figure 14, it appears that segregation is rate controlling in the first stage of screening and that all three stages can be



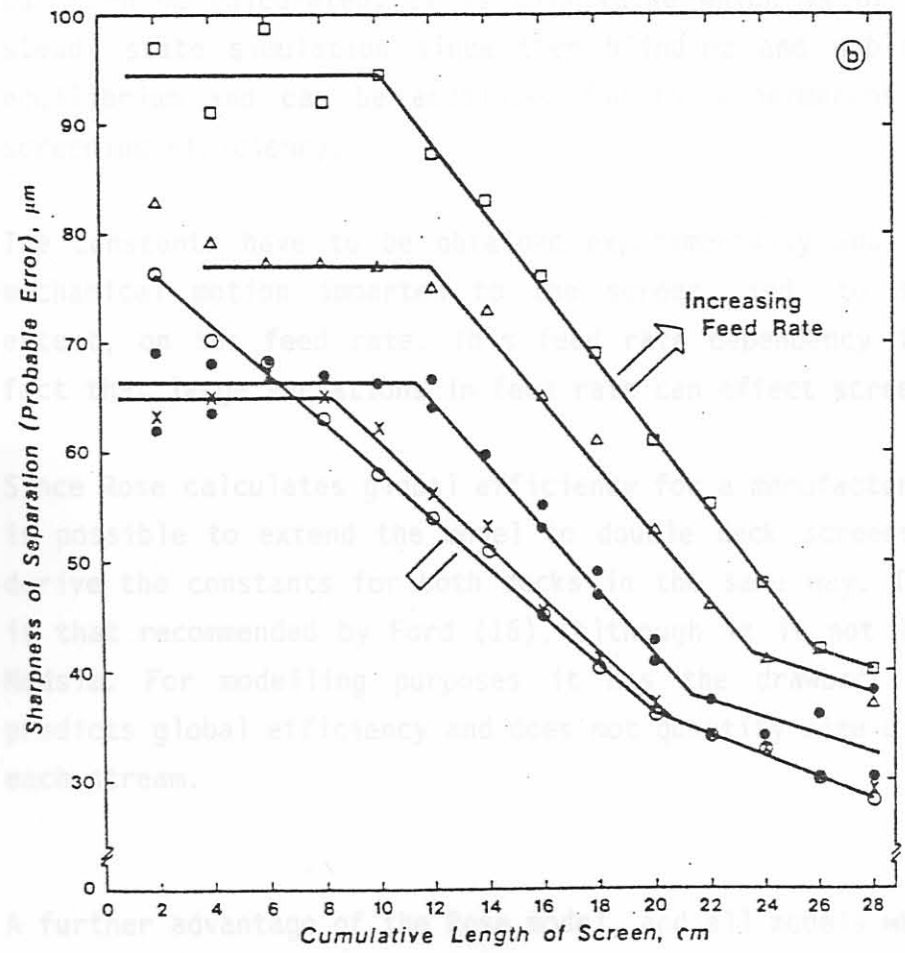


Fig 14 Data of Brereton and Dymott

represented by a first order equation. The model of Brereton & Dymott also has the same limitations as the Ferrara, Preti & Schena model in that it requires separate test equipment and cannot easily be expanded to double deck screening. These two models are, however, the most comprehensive studies of screening phenomena across the length of the screen.

The phenomenon of blinding of a screen has been neglected in the two-process models. English (10) identifies three constants in his screening model, namely a blinding rate, an unblinding rate and a rate of passage of particles through the screen. These three constants are presented in an analogous way to diffusion. This work has been extended by Rose (49) who incorporates an empirical equation to determine equilibrium efficiency of the screen. This empirical equation closely follows the solution of the differential equation he derived for screening, using the three 'diffusion coefficients' for blinding, unblinding and passage through the screen. Rose also indicates how these three constants may be calculated from a simple screening test where the underflow and overflow are measured as a function of time starting with a clean screen. Equilibrium efficiency can then be calculated. It is this value which is of importance in steady state simulation since then blinding and unblinding are in equilibrium and can be accounted for by a permanent reduction in screening efficiency.

The constants have to be obtained experimentally and depend on the mechanical motion imparted to the screen, and, to a much lesser extent, on the feed rate. This feed rate dependency is due to the fact that large variations in feed rate can affect screen motion.

Since Rose calculates global efficiency for a manufactured screen, it is possible to extend the model to double deck screens too, and to derive the constants for both decks in the same way. The Rose model is that recommended by Ford (16), although it is not implemented in Modsim. For modelling purposes it has the drawback that it only predicts global efficiency and does not quantify size distribution in each stream.

A further advantage of the Rose model, and all models which calculate global efficiency, is that once the efficiency of a deck has been

established, screenability characteristics tests, such as those detailed by Sullivan (52), can be used to determine the screening efficiency expected when screening a different material on the same screen. This screenability characteristics test calculates the percentage change of efficiency for a change of material on the same screen, using a laboratory test.

Although Rose has not tested his model in wet screening applications he indicated in commentary on his paper that he expected the model would be valid in these conditions but that the diffusion constants would change.

It has already been mentioned that the size distribution of run-of-mine was unknown and well-nigh impossible to measure. Rock fragmentation models related to blast design have been developed although geological variations affect the precision of these models. The Rammler-Kuznetsov model recommended by Cunningham (9) uses the Kuznetsov equation for mean fragment size of blasting products and a Rosin-Rammler equation for the size distribution of the fragments. This model is empirical, and the equation for the exponent, n, is one obtained by Cunningham.

The Kuznetsov equation, for very hard rock and for the explosive ANFO can be written as:

$$x=14,2695(V/Q)^{4/5}Q^{1/6}$$

where x=mean fragment size in cm
V=(burden)(spacing) (bench height) in m^3
Q=mass of ANFO per blasthole in kg

The Rosin-Rammler exponent, n, is based on fragmentation analysis, and is obtained from the following equation:

$$n=(2,2-14B/d)(1-w/B)(1+(A-1)/2)L/H$$

where B=burden in m
d=hole diameter in mm
w=standard deviation of drilling accuracy in m
A=spacing to burden ratio
L=charge length above grade in m
H=bench height in m

The representative size for the Rosin-Rammler distribution can now be obtained from x and n.

It is this Rosin-Rammler distribution which will be used to estimate the size of run-of-mine when simulation of the preliminary comminution units is attempted.