CRUSHING AND SCREENING MODELS FOR SIMULATION

by

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ABSTRACT

Accurate crushing and screening models are essential for the meaningful simulation of ore dressing plants such as the iron ore beneficiation plant studied in this work.

Crushing and screening models were studied, developed and enhanced. The basic simulator used was Microsim, which was subsequently expanded to incorporate these new models. The models were then evaluated individually. The Whiten crushing model was modified for haematite, as this is a particularly hard ore. A new model was developed for the gyradisc crushing of haematite, with two interparticle breakage mechanisms taking place in the crushing chamber. The gyradisc model has only the crusher closed side setting as parameter. Both models showed good agreement with experimental data. The Karra screen model was enhanced to include the use of 'poly' decks and non-square screen apertures, as used on the plant. The Rose efficiency model was developed to use efficiencies from plant data or experiments. The Rose model showed a better relative accuracy than the entirely empirical enhanced Karra model. The screen models developed can be used for different ores but the crushing models are not transferable.

Thereafter simulation was done for the quaternary sub-plant manufacturing two or three products respectively. The product ratios obtained by simulation were accurate in both cases. The optimisation routine was then used to calculate an improved fine to lumpy ore ratio. It was found that only a small improvement could be achieved in the quaternary plant. Simulation of the preliminary comminution plant, however, failed to give accurate results. This plant does not operate in steady state, therefore the error could be ascribed to this. The accuracy of the Nordberg gyratory crushing model used in this sub-plant could not be established. The washing and screening plant was successfully simulated with the new screening models.

The choice of size classes was found to be very important in the simulation of crushing and screening circuits. The maximum number must be used and should coincide with screen apertures. Microsim has proved to be a powerful simulator subject, to the quality of input data and evaluative skills of the user.

SAMEVATTING

Betroubare breker- en sifmodelle is noodsaaklik vir die betekenisvolle simulasie van ertsbereidingaanlegte, soos die ysterertsveredelingsaanleg wat hierin bestudeer is.

Breker- en sifmodelle is bestudeer, ontwikkel en verbeter. Die basiese simulator wat aangewend is, is Microsim, wat vervolgens uitgebrei is om nuwe modelle te inkorporeer. Die modelle is individueel geëvalueer. Die Whiten brekermodel is gewysig vir hematiet, aangesien dit 'n besondere harde erts is. 'n Nuwe model vir gyradisc vergruising van hematiet is ontwikkel, waarvolgens twee interpartikel breekmeganismes in die brekerkamer plaasvind. Die gyradisc model het slegs toekantstelling as parameter. Albei modelle toon goeie ooreenstemming met eksperimentele data. Die Karra sifmodel is uitgebrei om die gebruik van 'polydekke' en nie-vierkantige openings in te sluit. Die Rose effektiwiteitsmodel is ontwikkel om aanleg- of eksperimentele sifeffektiwiteite te kan gebruik. Die Rose model toon 'n beter relatiewe akkuraatheid as die empiriese uitgebreide Karra model. Die sifmodelle kan vir verskillende soorte ertse gebruik word, maar breker-modelle is nie oordraagbaar nie.

Hierna is simulasie vir die kwaternêre subaanleg, waar twee of drie produkte vervaardig word, uitgevoer. Die produkverhoudings verkry deur simulasie is akkuraat vir albei gevalle gevind. Die optimeringsroutine is aangewend om 'n verbeterde fyn tot stukerts verhouding te verkry. Slegs 'n klein verbetering is in die kwaternêre aanleg verkry. Simulasie van die voorvergruisingsaanleg het nie akkurate resultate gelewer nie. Hierdie aanleg funskioneer nie in die gestadigde staat nie, gevolglik kan die fout hieraan toegeskryf word. Die akkuraatheid van die Nordberg wentelbrekermodel wat in die subaanleg gebruik is, kon nie bepaal word nie. Die was- en sifaanleg is suksesvol gesimuleer m.b.v. die nuwe sifmodelle.

Die keuse van klasgroottes is baie belangrik in die simulasie van vergruisings- en sifaanlegte. Die maksimum aantal klasse moet gebruik word en moet ooreenstem met sifopenings.

Microsim is 'n kragtige simulator en sinvolle aanwending is onderworpe aan die kwaliteit van die toevoerdata en die oordeel van die gebruiker.

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SYMBOLS

BC Broadbent-Callcott

CCP Coarse cyclone plant

CDP Coarse drum plant

CSS Closed side setting

d50 Separation size

Epm Ecarte probable moyen

F Fine ore product

FCP Fine cyclone plant

IWI Impact work index

L Lumpy ore product

MDP Medium drum plant

OSS Open side setting

RR Rosin-Rammler

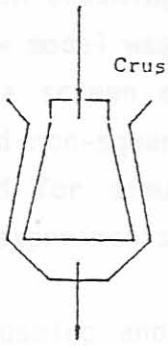
SP1 Sub-plant 1: Preliminary comminution of run-of-mine

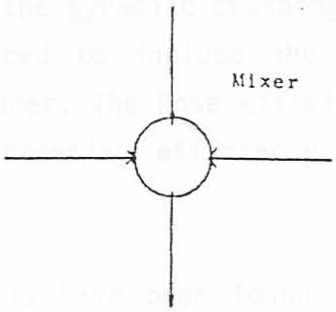
SP2 Sub-plant 2: Washing and screening plant

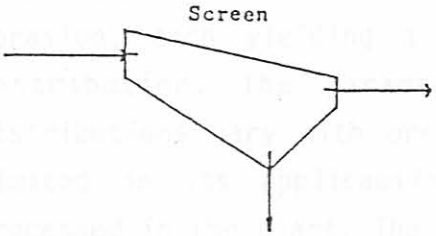
SP3 Sub-plant 3: Beneficiation plants (CCP, CDP, FCP, MDP)

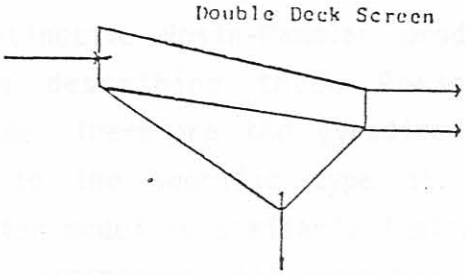
SP4 Sub-plant 4: Quaternary crushing and screening plant

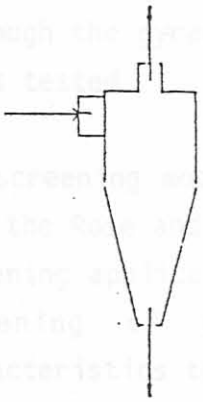
ICONS

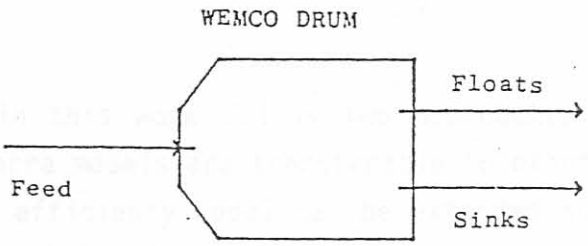












1 OVERVIEW OF RESULTS

In this work four models were entered into the Microsim unit library. The Whiten crushing model was modified for the crushing of haematite and a new model was developed for the gyradisc crushing of haematite. The Karra screen model was enhanced to include the use of 'poly' decks and non-square screen apertures. The Rose efficiency model was developed for simulation where screening efficiency is known from data or experiments.

These crushing and screening models have been found to be accurate for the simulation of the sub-plants, and are in good agreement individually with experimental data.

A study of gyradisc product size distributions revealed that there were two breakage mechanisms occuring in the crushing chamber. These mechanisms were interparticle comminution by compression and by abrasion, each yielding a distinctive Rosin-Rammler product size distribution. The parameters describing these Rosin-Rammler distributions vary with ore type. Therefore the gyradisc model is limited in its applicability to the specific type of iron ore processed in the plant. The Whiten model is similarly limited to the crushing of haematite, as model parameters will vary for different ores.

Crushing applications can be modelled with reasonable accuracy by considering only crusher settings and ore breakage characteristics. Only if operating conditions differ markedly from normal, must operating conditions be taken into account. Feed rates should remain within manufacturers' specifications for accurate simulation, although the gyradisc model can be used over the entire range of feed rates tested.

The screening models developed in this work follow two approaches. Both the Rose and the enhanced Karra models are transferable to other screening applications. The Rose efficiency model can be extended to screening of different materials by using screenability characteristics tests.

The Rose model is more accurate than the enhanced Karra model, but relies on data obtained from screening operations on similar

machines. It is the responsibility of the user to ensure that efficiencies input to the simulator correspond with recorded flow rates. If necessary, efficiencies should be modified, preferably using experimental data for the efficiency at the simulated flow rate. This is particularly important when the optimisation facility is used.

Simulation studies on the quaternary plant showed that Microsim was capable of simulating accurately the product from this sub-plant, both when there were two products (lumpy and fine ore) and when there were three products (lumpy, fine and direct reduction ore). The overall production ratios predicted were within two percent of those observed on plant.

A sensitivity analysis of variables on the quaternary plant revealed that the ratio of ore produced was most sensitive to changes in the values of the closed side settings of the fresh feed and recirculating feed crushers and less sensitive to changes in screen apertures. Changes in screen apertures could cause a significant proportion of the products to be beyond specification.

The optimisation facility of Microsim was then used for improving the ratio of lumpy to fine ore in the quaternary plant. The target ratio was taken as 25:75, the overall plant target. The optimisation variables were taken to be the closed side settings of the fresh feed crusher and the recirculating feed crusher. This optimisation study revealed that only a slight improvement of this ratio could be achieved in the quaternary plant, indicating that this plant is operating close to its optimum. Physical considerations were used to constrain the values of the optimisation variables.

In order to improve the ratio of lumpy to fine ore beyond the abovementioned optimum, modifications would have to be made in the preliminary comminution section of the plant (sub-plant 1).

Simulation of this preliminary comminution sub-plant was however not accurate. This could be ascribed to the fact that this sub-plant is fed by tip-trucks and therefore does not operate in steady state conditions. Microsim is a steady state simulator, hence its use in simulating this sub-plant (or any other application where steady-state conditions do not prevail) should be avoided. The accuracy of

the Nordberg gyratory crushing model was not established, and could be a source of error.

The washing and screening plant (sub-plant 2) was accurately simulated using the new models in Microsim.

Accurate simulation of crushing and screening applications depends on the careful choice of size classes. The maximum number of size classes should be used. If necessary this maximum (set at 20 in the standard version of Microsim) may be increased by editing and recompiling the Microsim program. Size classes should preferably be chosen to coincide with screen apertures in simulation studies. It is not possible to do this when using the optimisation routine with screen apertures as optimisation variables. The user should be aware that this may affect the accuracy of the optimisation. It is also wise to perform several optimisation runs, varying step changes of the optimisation variables, in order to detect premature termination of the optimisation routine.

Microsim is a useful tool for simulation and optimisation of ore dressing flowsheets. The process engineer can use Microsim to assess inexpensively the effect of changes to the plant. New units can also be designed using the optimisation facility. Good quality input and careful evaluation of results are, however, essential to successful application of Microsim.

2 INTRODUCTION

2.1 Introduction to ore dressing simulation

With the advent of high speed digital computation, computer simulation has become a valuable tool to understand and analyze industrial processes.

Ore dressing has lagged behind the chemical process industries in the field of simulation because of the difficulty of handling a material particle size distribution in calculation procedures. Nevertheless, ore dressing simulators have developed in the last decade to be of great value in all stages of plant development.

In initial stages of plant design, the process and economic feasibility of various alternative flowsheets and unit sizes can be evaluated using models not dependent on empirically derived data. Thereafter, simulators can be used with more reliable data and/or models in pilot plant scale operation. Hence optimum operation of full scale plants can be determined by repeated simulation. Likewise, design and parameter estimation can be done by repeated simulation, using simple models for convergence and complex models for the final design. Some simulators have the capability to do repeated simulation using an optimisation algorithm.

During normal operation of the full scale plant, simulators are used to optimise plant performance, to determine the influence of variable or parameter changes and to determine the parameter changes required for new products, without doing any on-plant trials or making use of cumbersome hand calculations. Such usage is an important aim of the ore beneficiation plant.

The simulator can be used to estimate parameters of a particular material, unit operation from plant data and to develop alternative models of unit operations. The development of primarily crushing and screening models will be dealt with in this work.

The implementation of control strategies is facilitated through the use of a simulator, particularly if a dynamic simulator is used or a model developed from first principles, since plant behaviour is then known and plant response can be predicted.

Simulators are used for the training of plant personnel to run the plant proficiently as well as to prevent costly errors occurring. This serves as a vehicle for technology transfer from a research environment to the plant.

Since supervisory control of the plant is envisaged, simulation studies would be significant in the development of control strategies.

To use a general purpose simulator efficiently on a given plant, it is necessary to enhance it using a combination of theoretical and empirical modelling and historical data. In this work, a general purpose simulator, Microsim (8,34,50,51), is upgraded for application as a cheap and effective means of simulating the plant for a variety of purposes.

Simulation of entire plants is usually restricted to simulation of steady state operation only in order to reduce the complexity of the problem. The scope of this work is therefore limited to steady state simulation only.

2.2 Introduction to the ore beneficiation plant and simulation thereof

The ore beneficiation plant produces two (or sometimes three) products of concentrated iron ore from run-of-mine viz. lumpy, fine and, if required, direct reduction ore. The ore sizes for the three products are as follows:

Ore	Size (mm)
Lumpy	25/8
Fine	5/2
Direct Reduction	11/5

The production percentages and tonnages will vary according to market demand.

If direct reduction ore is not required, this material is crushed to fine ore and plant parameters are changed to maintain a better ratio of fine to lumpy ore. Ideally, the ratio of fine to lumpy ore should be 1:3, but to date the best ratio achieved has been 2:3.

A method is required to quantify plant performance, and hence to provide a means of plant optimisation according to the production percentages and tonnages required.

The metallurgical optimisation and maintenance of standards is the primary aim of simulation of the plant. However, minimization of waste (and hence lowered cost of land rehabilitation) is a secondary aim.

The plant can be considered as four separate sub-plants:

(1)Preliminary comminution of run-of-mine (SP1)
(2)Washing and screening (SP2)
(3)Beneficiation of four size fractions for ore (CDP, MDP, CCP, FCP)
(4)Crushing and screening of ore to products (SP4).

These sub-plants are shown schematically in figures 1 to 7, as Microsim flow diagrams detailing only the metallurgical flow and representing parallel units as one. All ancillary equipment is not

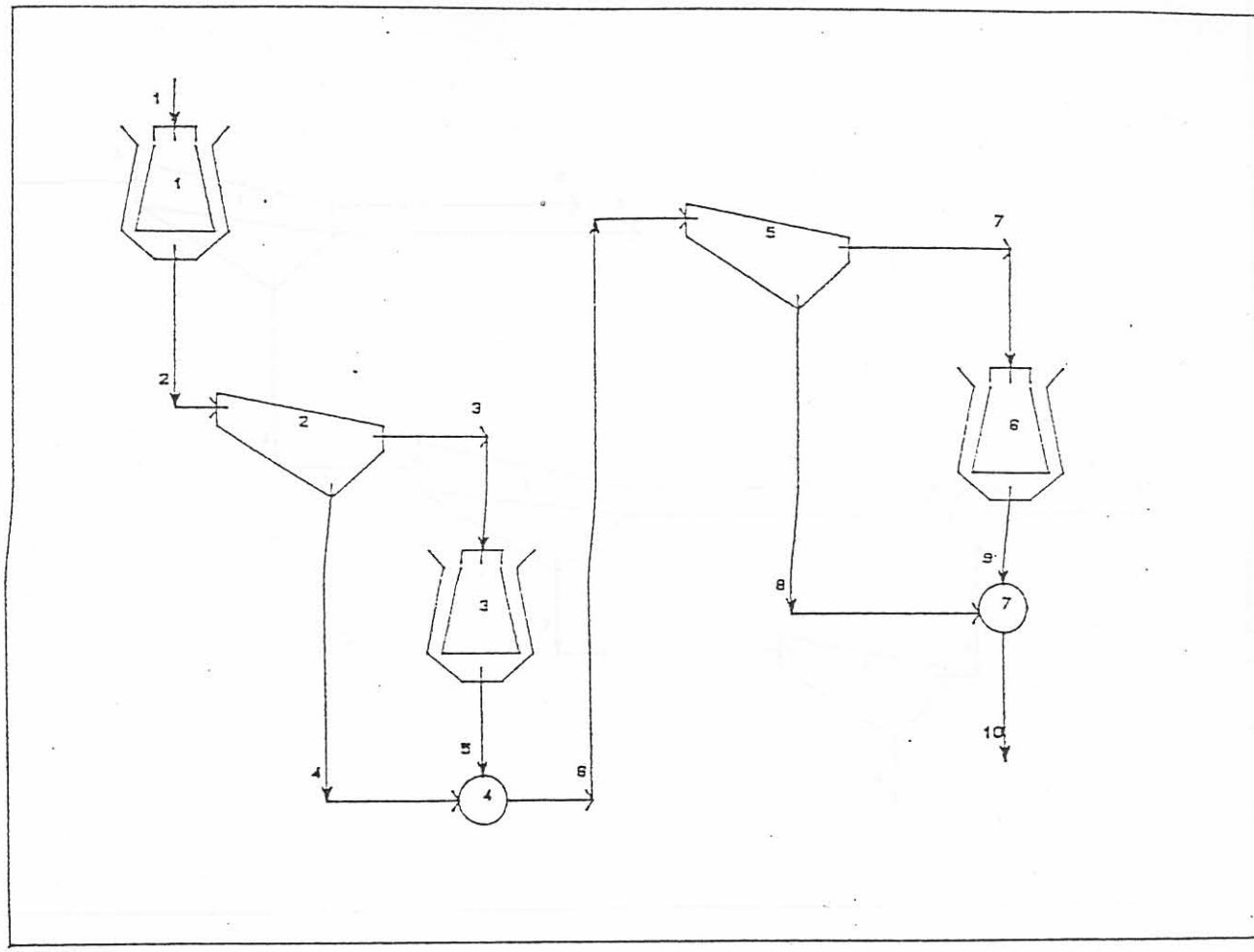


Fig 1 Flow diagram for sub-plant 1: Preliminary comminution

Unit 1: Primary gyratory crusher, OSS = 225mm
Unit 2: Grizzly, Aperture = 120 x 120mm
Unit 3: Secondary Symons cone crusher, CSS = 90mm
Unit 5: Grizzly, Aperture = 80 x 80mm
Unit 6: Tertiary Symons cone crusher, CSS = 50mm
Units 4 and 7: Mixers

Stream 10 corresponds to stream 1 of SP2

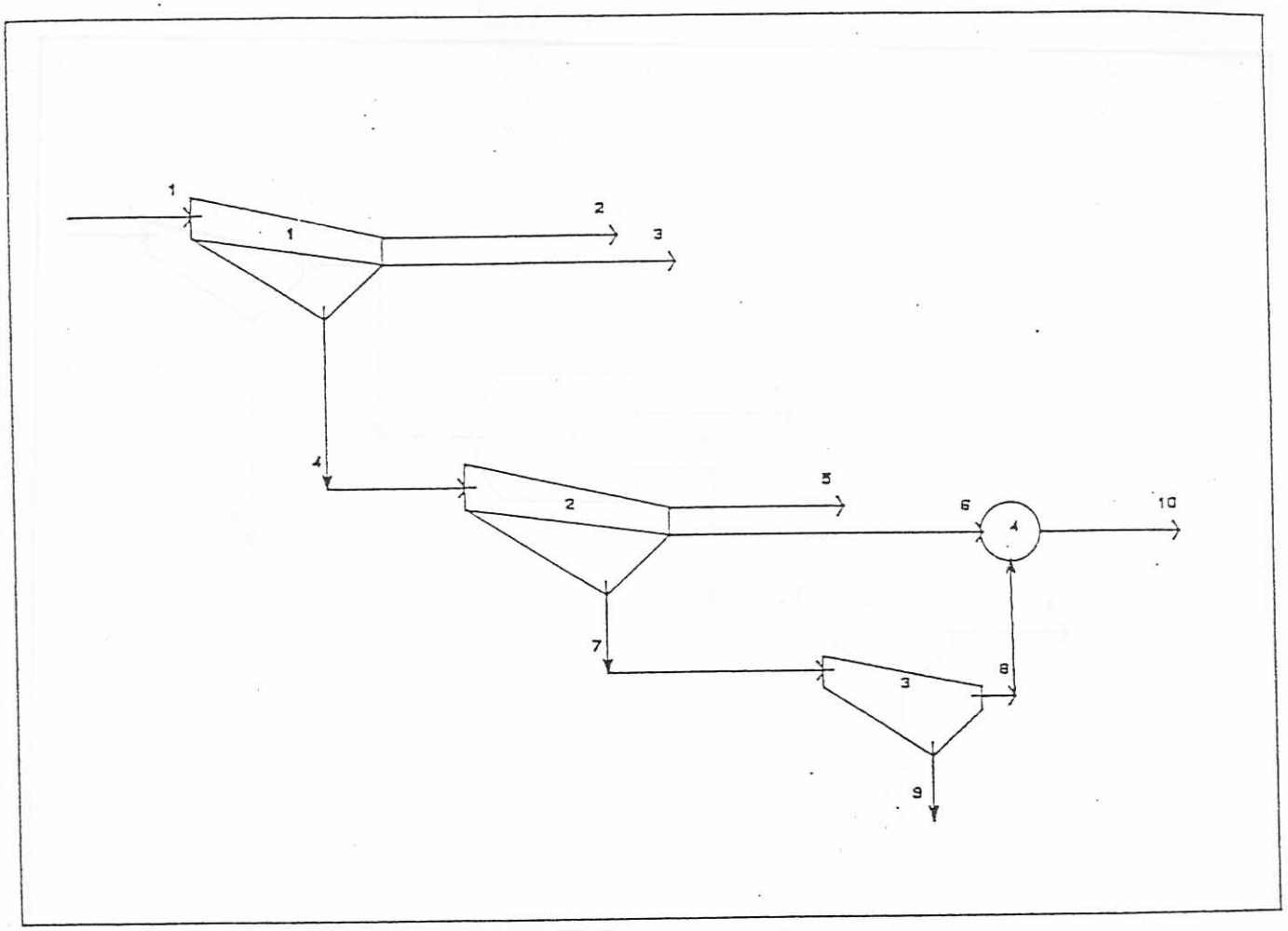


Fig 2 Flow diagram for sub-plant 2: Washing and screening

Unit 1: Primary screen, Top deck aperture = 26,2 x 26,2mm
Bottom deck aperture = 10 x 10mm
Unit 2: Secondary screen, Top deck aperture = 6,3 x 6,3mm
Bottom deck aperture = 1,75 x 12mm
Unit 3: Dewatering screen
Unit 4: Mixer

Stream 2 corresponds to stream 1 of CDP
Stream 3 corresponds to stream 1 of MDP
Stream 5 corresponds to stream 1 of CCP
Stream 10 corresponds to stream 1 of FCP

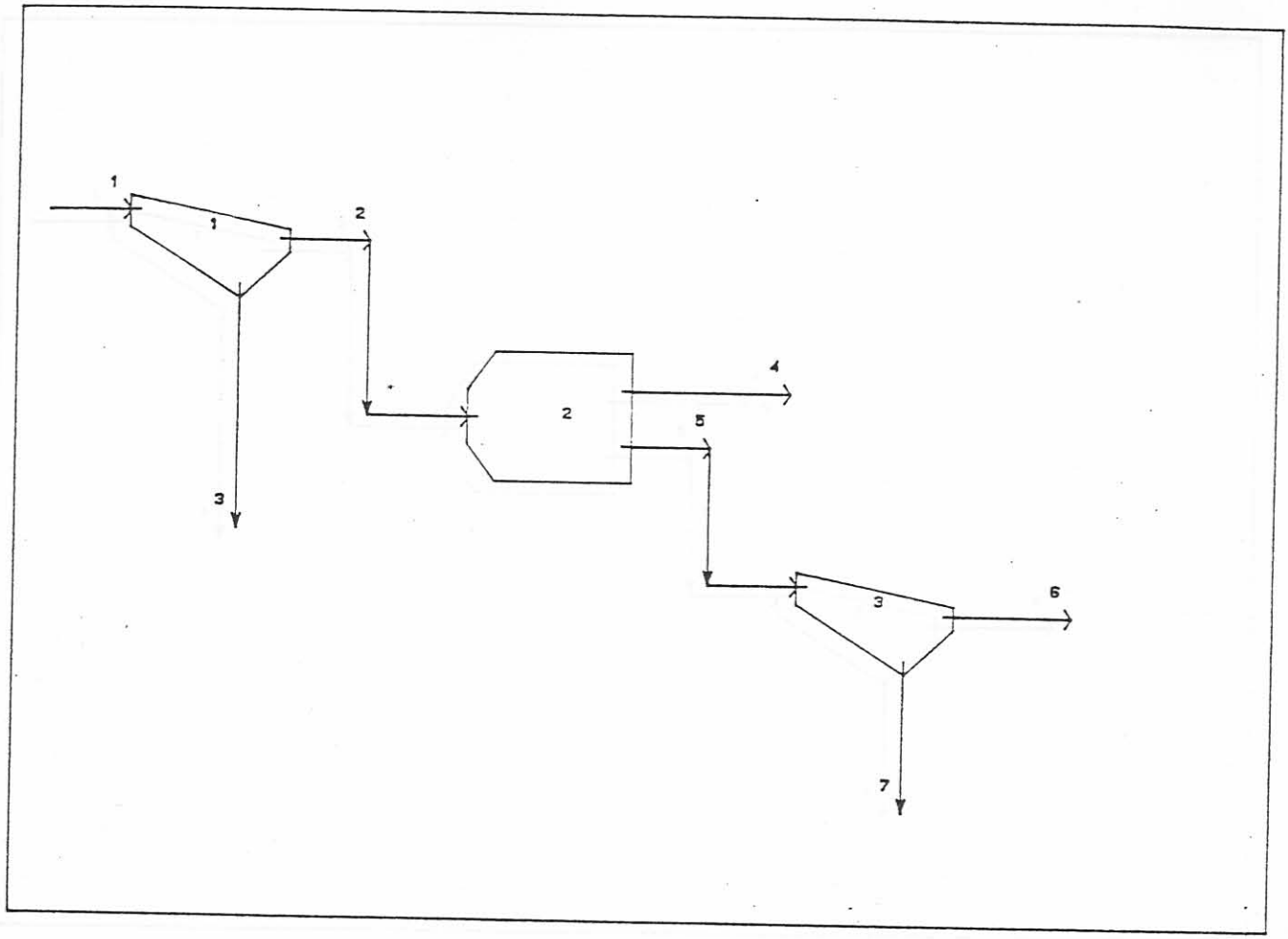


Fig 3 Flow diagram for the coarse drum beneficiation plant.

Unit 1: Feed preparation screen, aperture = 4,5 x 35mm
Unit 2: Wemco drum separator, specific gravity = 3,8
Unit 3: Sinks screen, aperture = 2,7 x 33mm

Stream 6 corresponds to stream 1 of SP4

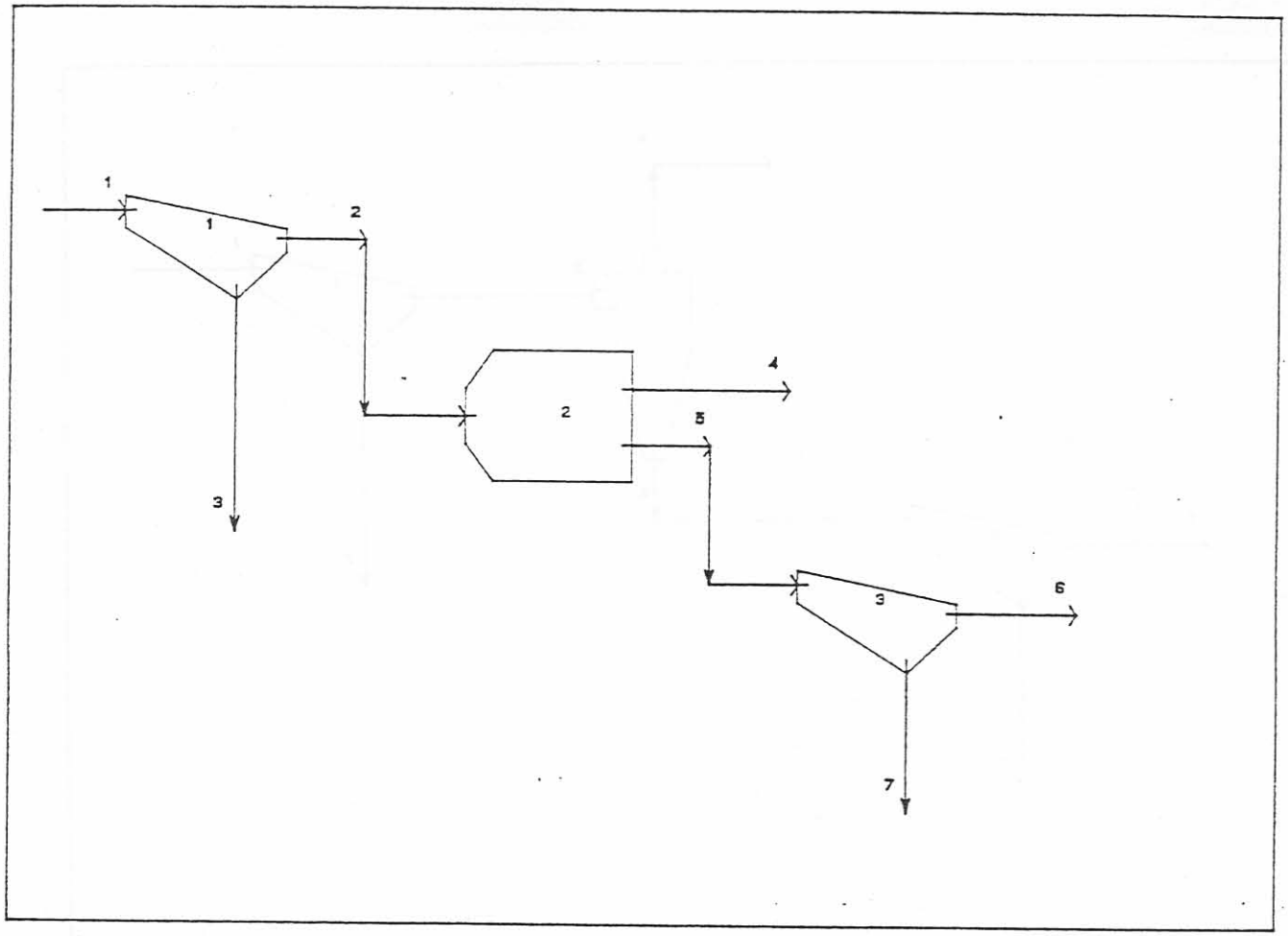


Fig 4 Flow diagram for the medium drum beneficiation plant

Unit 1: Feed preparation screen, aperture = 10 x 10mm
Unit 2: Wemco drum separator, specific gravity = 3,7
Unit 3: Sinks screen, aperture = 5 x 5mm

Stream 6 contains LUMPY ORE product

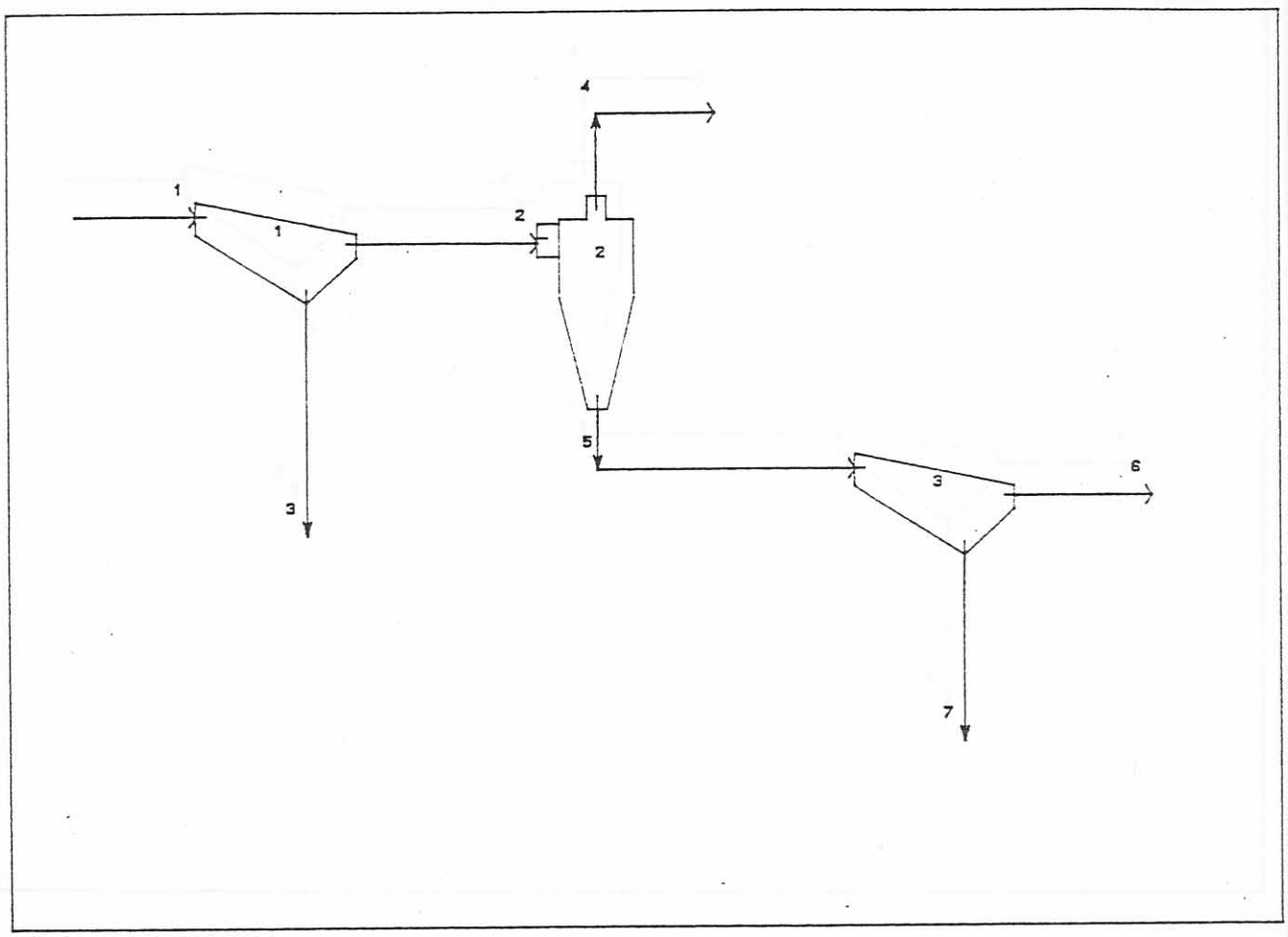


Fig 5 Flow diagram for the coarse cyclone beneficiation plant

Unit 1: Feed preparation screen, aperture = 3,15 x 3,15mm
Unit 2: Dense medium hydrocyclone, specific gravity = 3,1
Unit 3: Sinks screen, aperture =3,15 x 3,15mm

Stream 6 corresponds to stream 3 of SP4

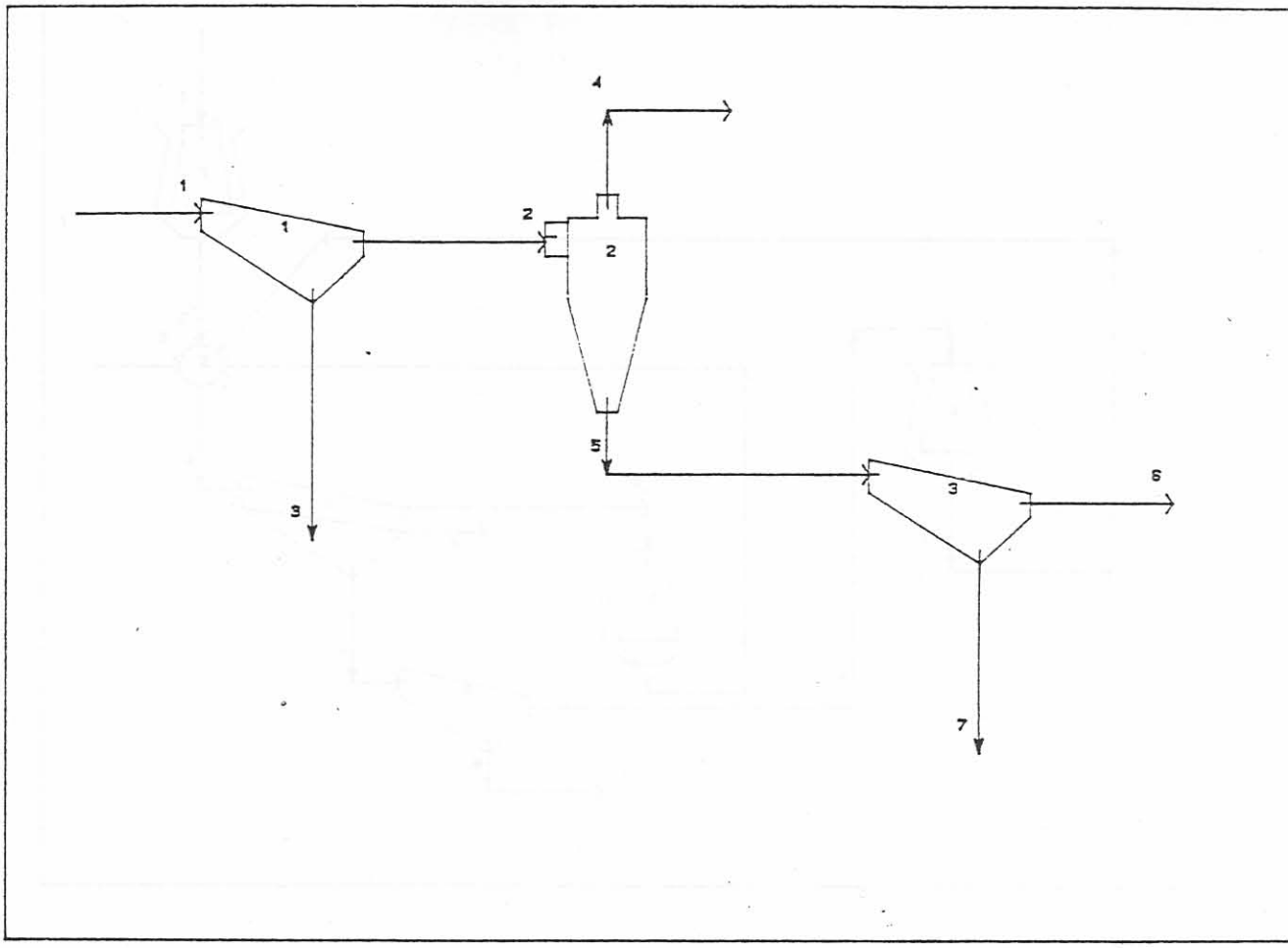


Fig 6 Flow diagram for fine cyclone beneficiation plant

Unit 1: Feed preparation screen, aperture = 0,63 x 12,5mm
Unit 2: Dense medium hydrocyclone, specific gravity = 3,1
Unit 3: Sinks screen, aperture = 0,63 x 12,5mm

Stream 6 contains FINE ORE product

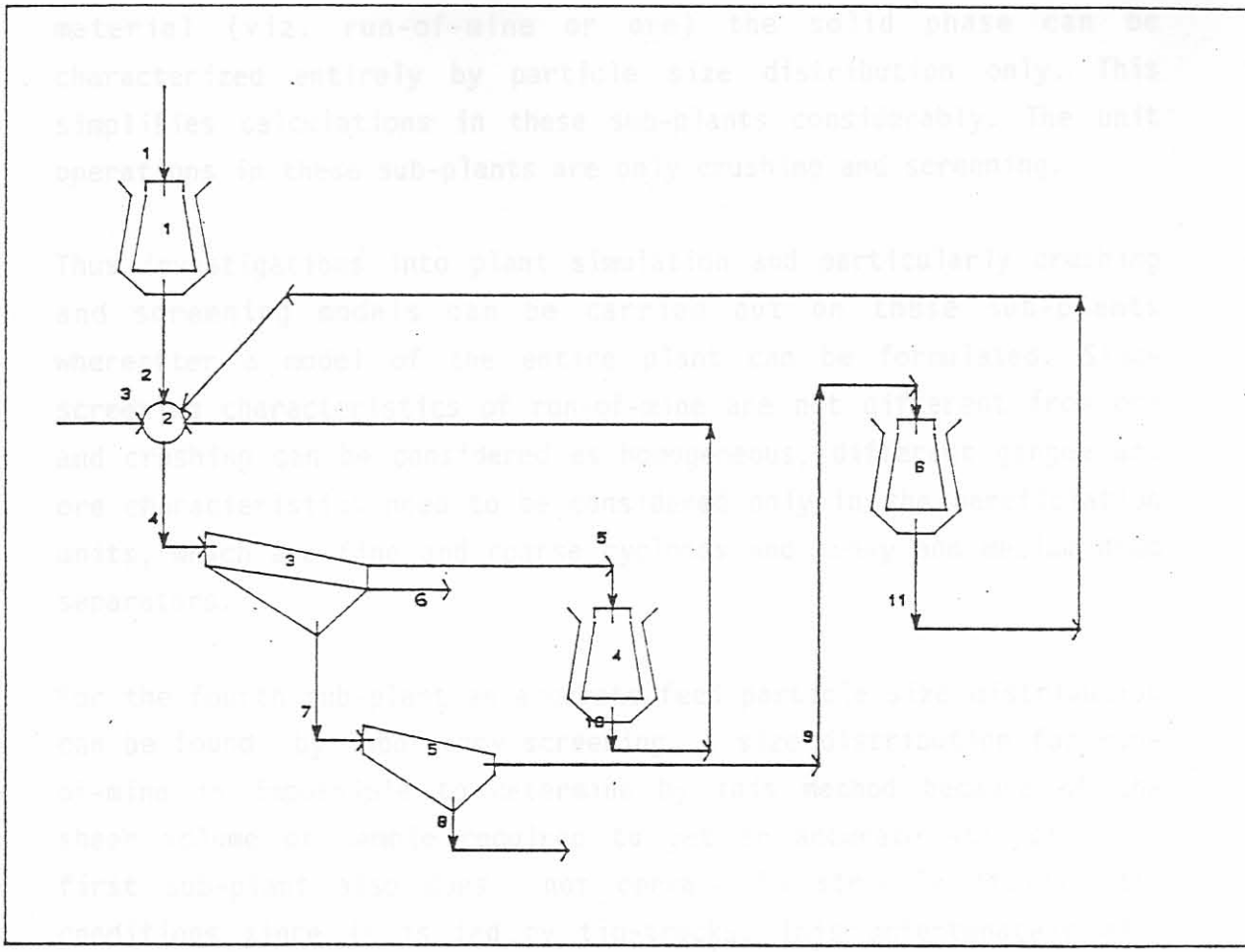


Fig 7 Flow diagram for sub-plant 4: Quaternary crushing and screening

Unit 1: Fresh feed shorthead crusher, CSS = 22mm
Unit 3: Primary screen, Top deck aperture = 25 x 25mm
Bottom deck aperture = 9 x 13mm
Unit 4: Recirculating feed shorthead crusher, CSS = 16mm
Unit 5: Secondary screen, Top deck aperture = 6,3 x 6,3mm
Unit 6: Gyradisc fines crusher, CSS = 9mm
Unit 2: Mixer

Stream 6 contains LUMPY ORE product
Stream 8 contains FINE ORE product

included. Figure 7 shows the configuration for the production of fine and lumpy ore. The configuration for production of three ores is given later.

Since the first, second and fourth sub-plants have only one grade of material (viz. run-of-mine or ore) the solid phase can be characterized entirely by particle size distribution only. This simplifies calculations in these sub-plants considerably. The unit operations in these sub-plants are only crushing and screening.

Thus investigations into plant simulation and particularly crushing and screening models can be carried out on these sub-plants whereafter a model of the entire plant can be formulated. Since screening characteristics of run-of-mine are not different from ore and crushing can be considered as homogeneous, different gangue and ore characteristics need to be considered only in the beneficiation units, which are fine and coarse cyclones and heavy and medium drum separators.

For the fourth sub-plant an accurate feed particle size distribution can be found by laboratory screening. A size distribution for run-of-mine is impossible to determine by this method because of the sheer volume of sample required to get an accurate analysis. The first sub-plant also does not operate in strictly steady-state conditions since it is fed by tip-trucks. This unfortunately also limits the validity of steady state simulation of this sub-plant.

Screening is of critical importance at the plant, since this is the mechanism whereby the three products are separated and products beyond specification are financially penalized. Largely through changing screens will the product specifications be met for varying production percentages, thus making prediction of screening performance essential. Furthermore, screen replacement from wear provides the only real opportunity for modification of the plant without incurring additional cost or further delay. Since it is impossible to change the most important parameter of screening, namely the deck, except by shutting down the plant, the better the screen model, the more accurate the choice of screen. A model which will show the effect of new types of screens without direct plant tests will be of great economic value. The effects of using moulded plastic decks (called 'poly' decks, as used hereafter) and non-square

(but still rectangular) screen apertures must be reflected in new models, as these decks are being used on the plant.

A very important consequence of plant modelling will be the application of the model in the envisaged control of the plant. Experience gained in modelling the plant can be usefully applied in the control project.

(Dynamic) Simulation studies of the plant will also enable optimisation of the use of tip-trucks by providing input to the computerized truck control system. This system currently only controls truck movement within the open-pit mine.

It is evident that a general purpose simulator for ore dressing operations is necessary. The simulator must be user-friendly and reliable, so that it can be used by plant personnel. Easy input of information to the simulator and documentation are essential.

If the simulator is modular it could be used for a great variety of flowsheets of other plants and be extended as new models are developed.

It must run on a computer system which is suitable for use in a mining environment and fairly inexpensive. Likewise the software should be easily expandable and inexpensive to maintain.

From experience with the Microsim users group, the following very important observations can be noted.

Plant engineers lose enthusiasm if the models they choose are unfamiliar and/or incorporate parameters with which they are unfamiliar (or are unmeasurable), even if these parameters are widely used in academic work. Likewise, design engineers prefer simple models with as few parameters as possible.

To overcome this, theoretical background of the models has to be supplied, together with estimates of parameters and/or detailed procedures of easy experiments to determine these parameters, using available equipment where necessary.

From the above it is obvious that models incorporated in the software

should not require tuning by plant personnel. Although this is a common practice in research environments, it should be discouraged as models using exact plant parameters and ore characteristics are more easily accepted by plant personnel and are more meaningful.

Error handling by the simulator must prevent the program from hanging or terminating incorrectly and must guard against impossible solutions. All belief in a simulator can be lost through this.

In this work, crushing and screening models are investigated so that meaningful simulation studies can be done to meet the aims mentioned above. Other Corporate centres will benefit from these models and the experience gained from the simulations. The models developed and modified are thus ones that the plant and design engineer can understand, the parameters for which can be determined in a laboratory or plant and require no new test equipment.

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.

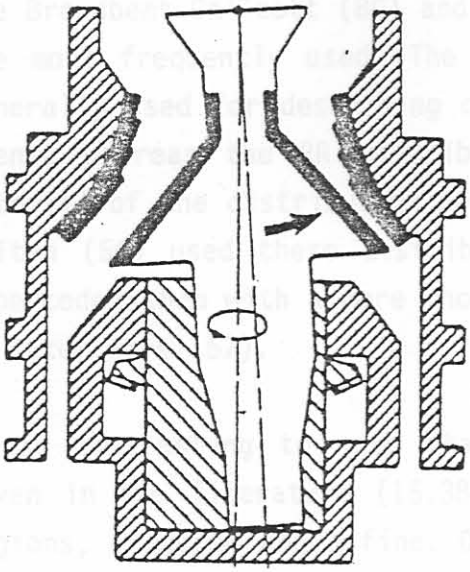
To date crushing has not been much modelled as crushing has been considered as a conditioning prior to grinding. Beyond empirical modelling by manufacturers, only Whiten's work (56,57) on cone crushers and its extension to shorthead crushers by Karra (27) incorporates a theoretical treatment.

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.

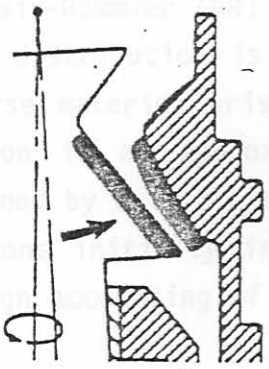
The most popular method of comminution modelling was to obtain a best fit curve through a plot of output size distribution from the crusher. This curve is usually only thought to be a function of the crusher closed side setting (CSS) and the impact work index (IWI) of the material. The manufacturers'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



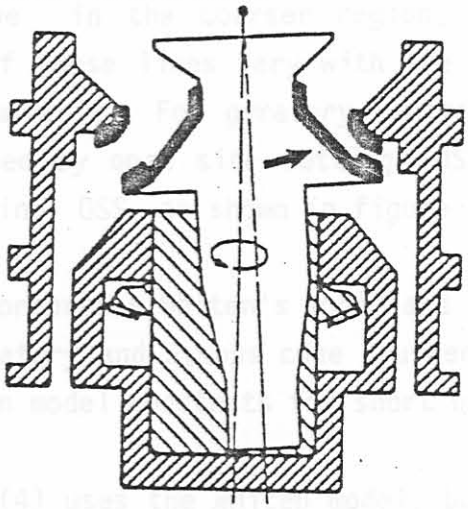
Cone

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.

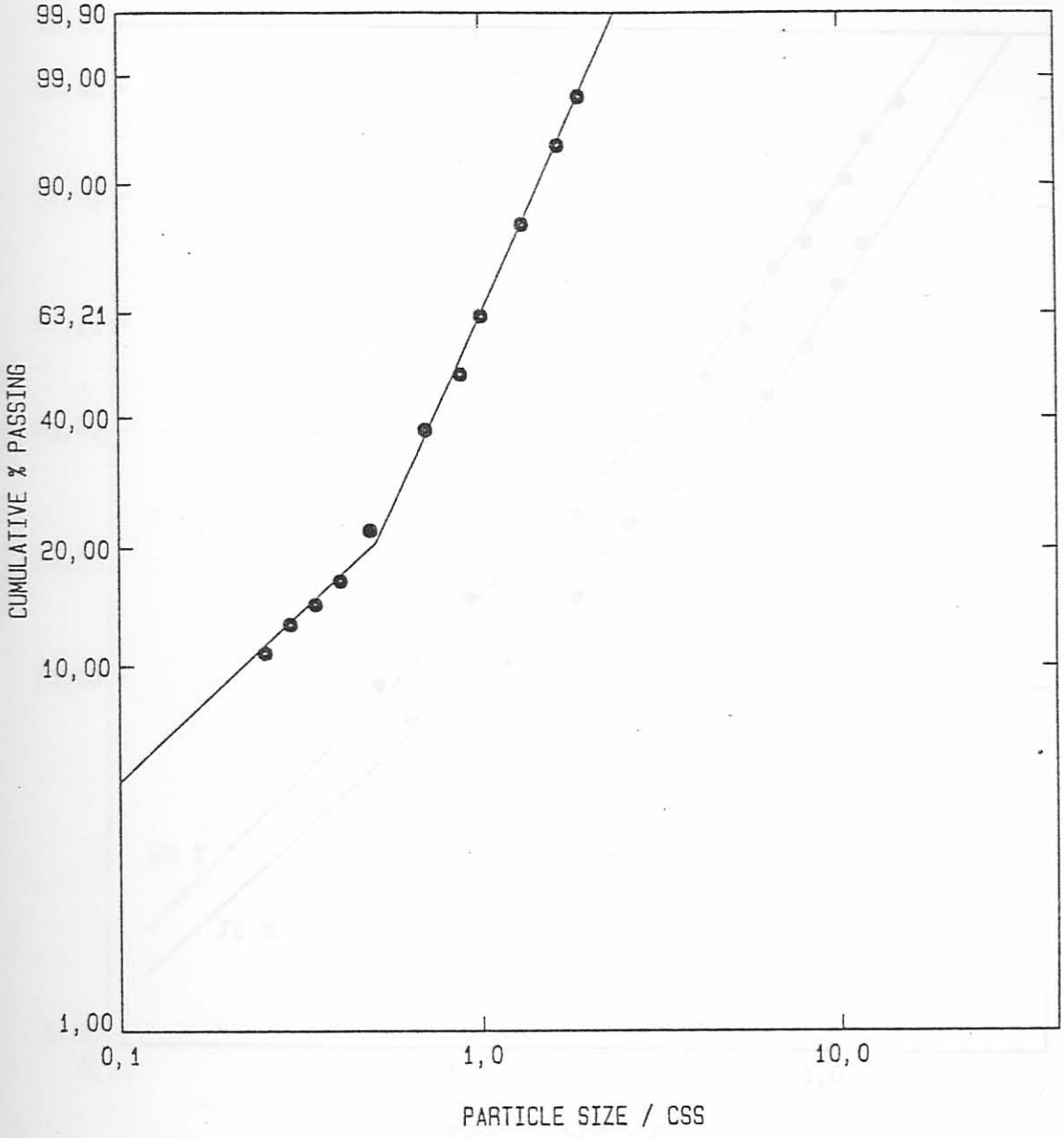


Fig 9 Rosin-Rammler plot for output from a Symons cone crusher

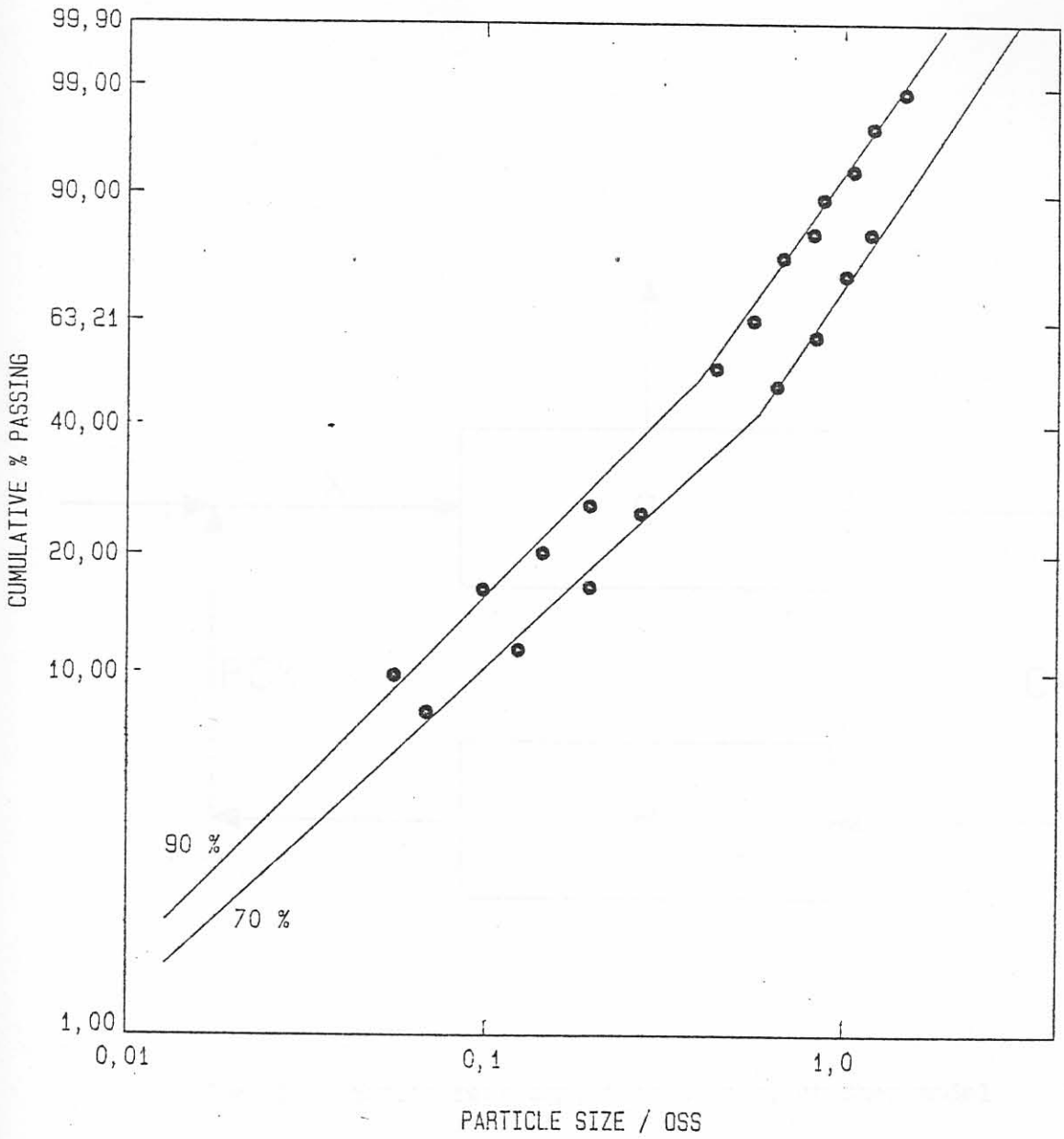


Fig 10 Rosin-Rammler plot for output from a gyratory crusher

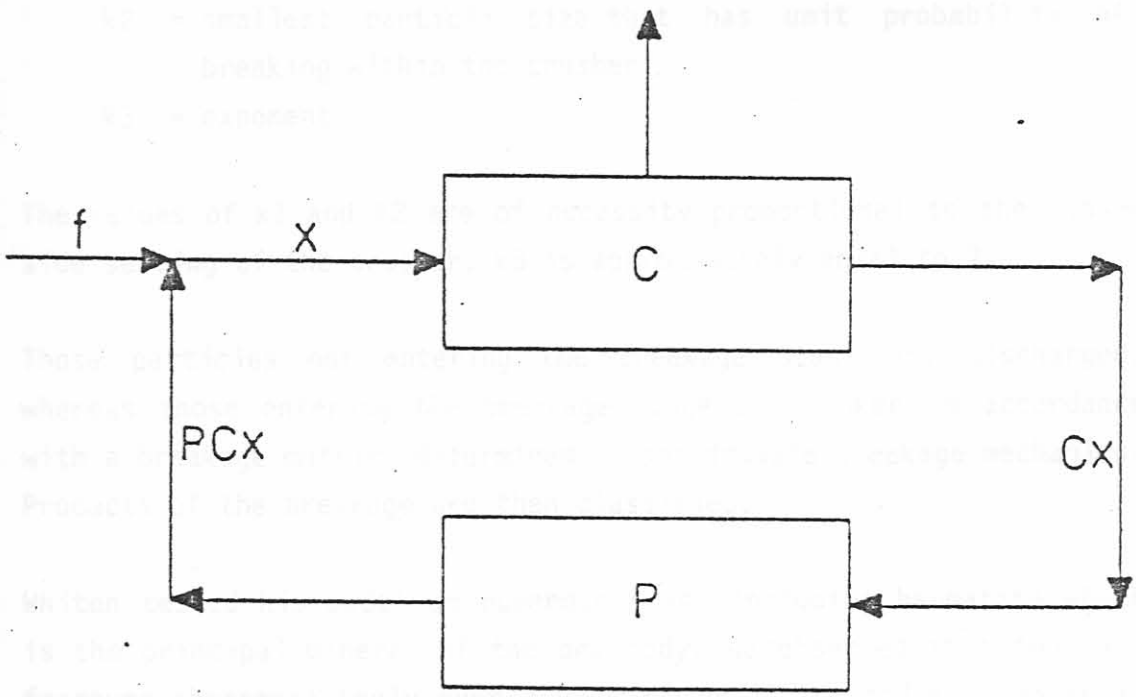


Fig 11 Symbolic representation of cone crusher model

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

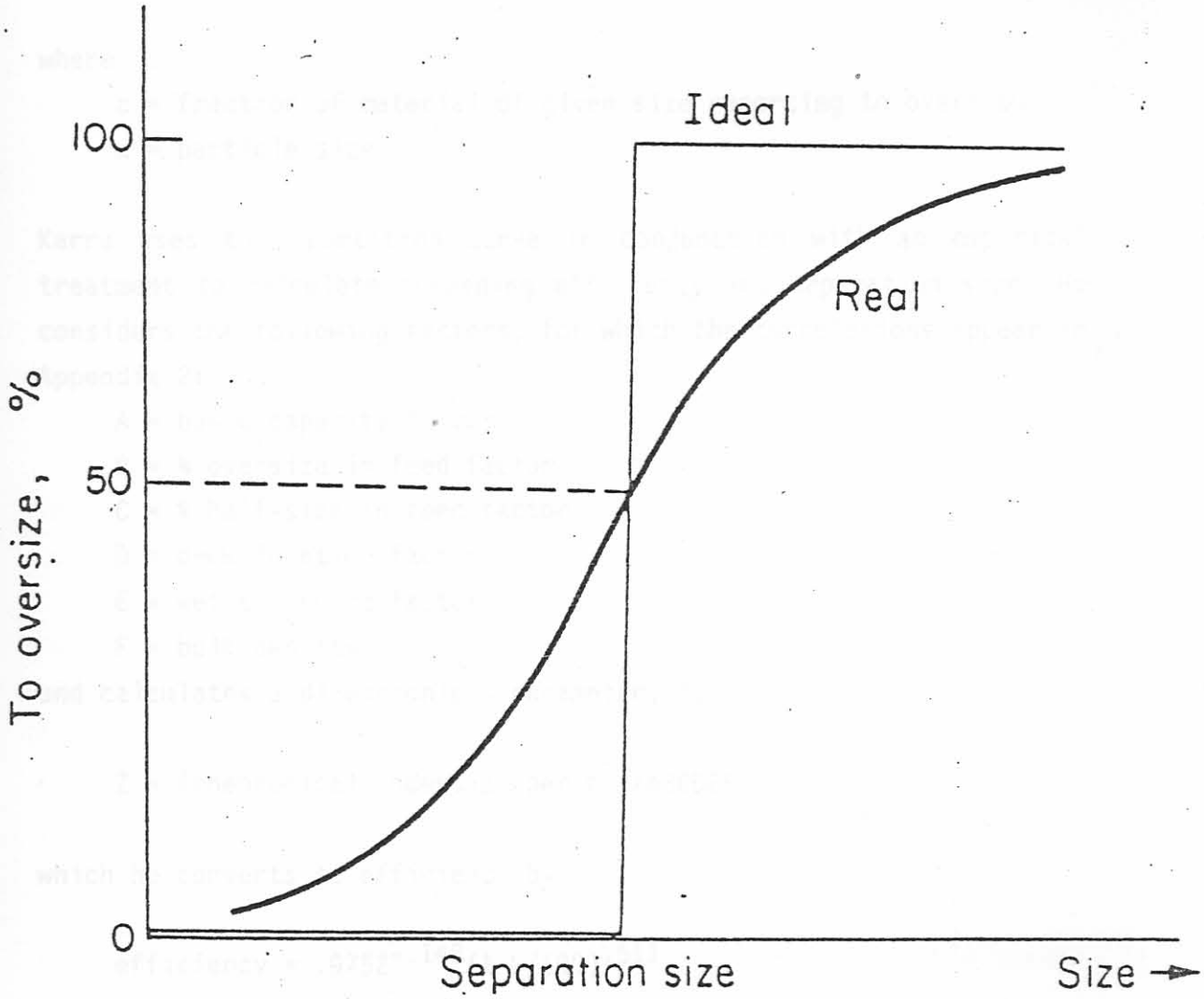


Fig 12 Partition curve

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.

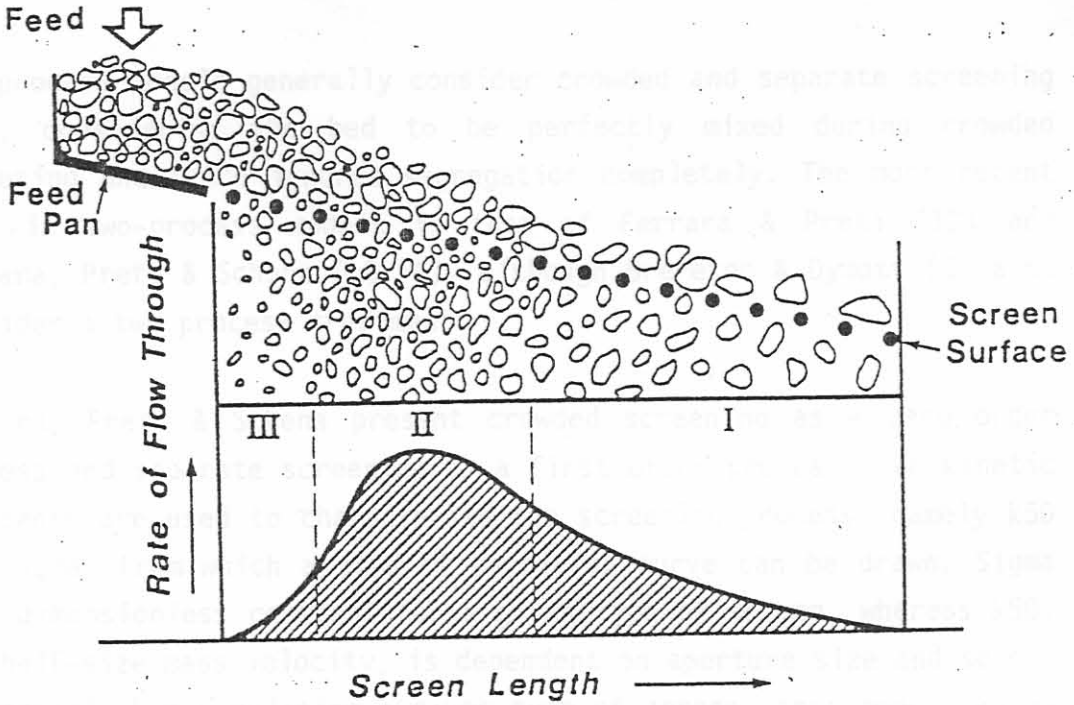


Fig 13 The three major regions occurring along a screening surface

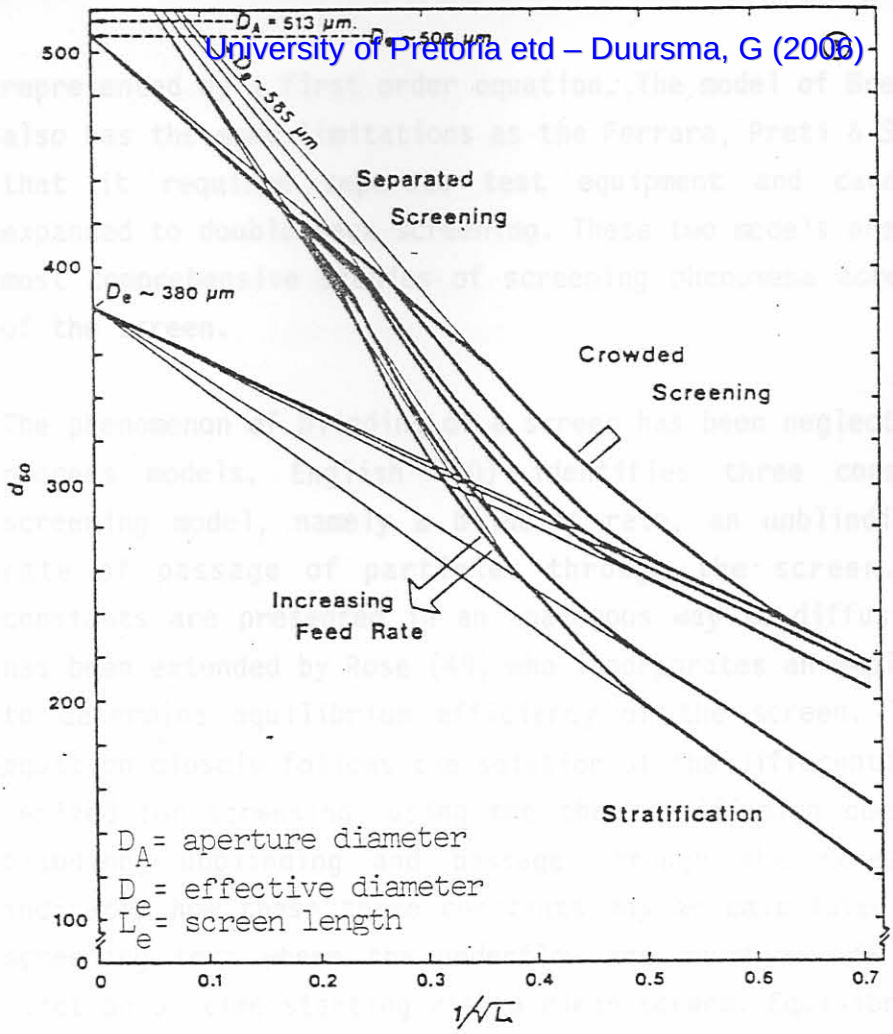
Despite the identification of three screening regions, much work has been done in which screening is considered as one process. Kelly and Spottiswood (29) document some of these one-process models and indicate the work of Miwa which identifies an equation relating the separation size (d50) to the inverse 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



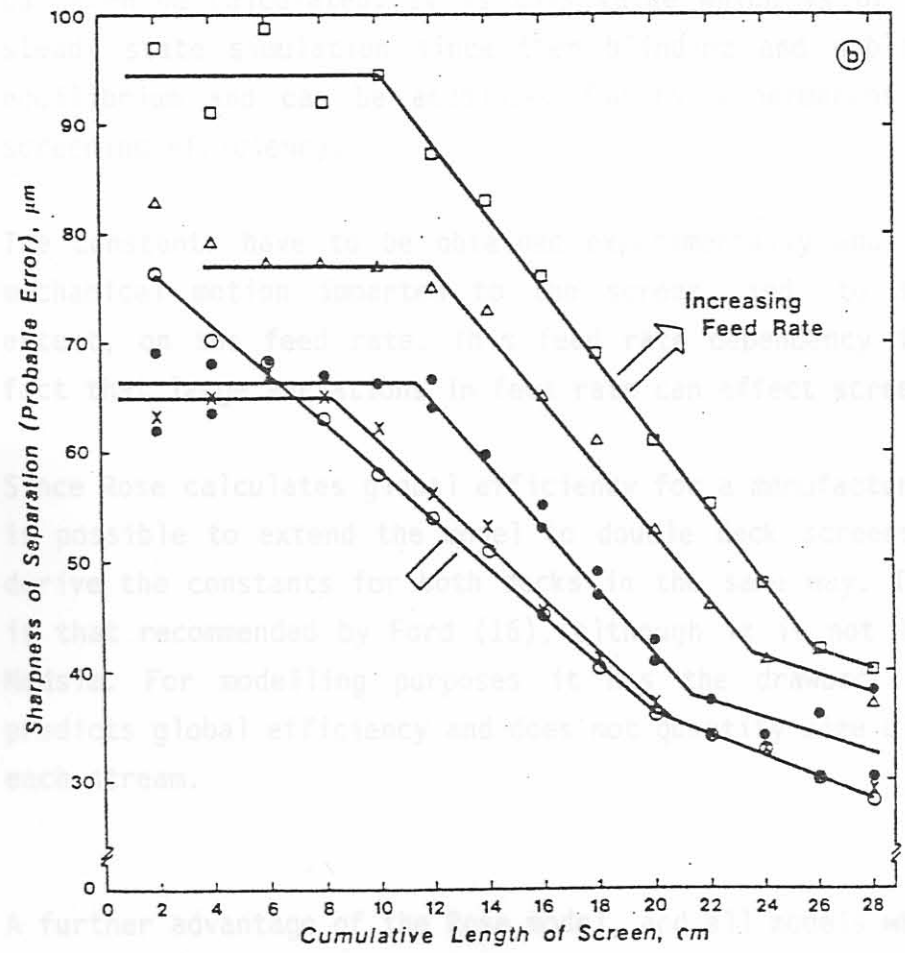


Fig 14 Data of Brereton and Dymott

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.

4 MODEL DEVELOPMENT

4.1 Microsim and model requirements

The Microsim unit library contains general models of most ore dressing unit operations. However, the plant we wish to simulate contains a gyradisc crusher for which no model exists. The existing screening models do not allow for the use of poly decks and non-square screen apertures, both of which are used on the plant. Furthermore, the ore to be treated is particularly hard and the generalised constants employed in the existing Whiten crushing model are inappropriate.

The following four models were thus incorporated into Microsim, to cater for the requirements of this plant:

a modified Whiten crushing model, programmed as overlay procedure CRUSH6_7, a semi-empirical model for crushing haematite

a new empirical Gyradisc crushing model, programmed as overlay procedure CRUSH5

an enhanced Karra screen model, programmed as overlay procedure SCREEN5, an empirical model for poly decks with non-square apertures

new Rose efficiency models, programmed as overlay procedures ROSE1 and ROSE2, using experimentally determined screening efficiencies.

All other unit models remain in the unit library, although the original Whiten model was deleted because of the limit on number of models per unit type. The Pascal listings for these models can be found in Appendix 3.

For the purpose of model development, crushing was considered homogeneous (i.e. crushing characteristics did not vary with grade) and screening was likewise considered uniform for all grades of material.

Microsim requires that models developed are programmed in a particular way (as outlined below) to fit the sequential modular

All models must have as input only one stream, and as output as many streams as are given by the icon for the unit type. For crushers, only one output stream is permitted, single deck screens have two and double deck screens have three output streams.

Each model has as input the complete feed stream array, and mass flow rate of the stream, together with model parameters. The model can also access system data (e.g. specific gravity of pure components).

The solution to each model is required to be the complete specification of the mass flow rates and stream arrays for each output stream. Thus the model must manipulate the input data according to given equations to give a solution of this form.

The models will be accessed as many times as determined by the ordering program. Upon completion of a simulation, the user may request graphical or tabular output of mass flow rates, size and grade distributions and/or partition curves, as appropriate.

The complete Pascal overlay procedures were inserted into the unit library (UNIT1.PAS for crushing models and UNIT2.PAS for screening models). The CASE statements in MODELS.PAS for crushers, single deck screens and double deck screens were updated, and the file OVERLAY.PAS was compiled to create a file SIMULATE.COM. The new model names were entered in the data file MODEL.DAT. The program DBASE was run to enter new model parameters as well as default values for these parameters. It is necessary to incorporate text for relevant questions into the database using this program. These questions (and default values) will then be displayed on the screen prompting the user to enter required data for a given flowsheet.

Microsim is now ready to be used as outlined in chapter 3.

4.2 Crushing models

4.2.1 Whiten model

The Whiten model (see section 3.3 for the theory) as written in Microsim was not suitable for use in its original form as the breakage characteristics were average values rather than those of a specific ore and crushing application.

The model parameters which must be entered by the user are the closed side setting, CSS, in metres, the fractional proportion of fines produced during breakage events, K, and the impact work index, IWI, in kWh/t. The impact work index for the iron ore is 26,4kWh/t. The value of K was found to be dependent on the breakage events occurring in the crusher.

The model has a breakage function with exponents m and n. These exponents are ore-specific. Whiten (57) has documented the values of exponents m and n for haematite. The value of m is given as 0,535. This value is close to the generalised value used in the original Microsim model of 0,5. The value of n is related to the number of breakage events in the crusher. For both Nordberg Symons cone crushers and shorthead crushers five breakage events occur. From the work of Whiten (57) on haematite it was found that this corresponded to a value for n of 2,0 (cf. 4,5 for the existing Microsim model) and an average value for K of 0,2. The parameter K depends on CSS and to a lesser degree on the feed rate to the crusher.

The algorithm for procedure CRUSH6_7 is as follows:

(1) determine total flow rate in each size class in the input stream

(2) from the smallest size class to the largest:

(2.1) calculate amount of material of size x classified from the classification function

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

where k1=0,653CSS for Symons crushers
k1=0,944CSS for shorthead crushers
k2=1,21CSS for Symons crushers

k2=1,722CSS+0,004826 for shorthead crushers
k3=2,0 for Symons crushers
k3=3,0 for shorthead crushers

and multiply by the mass in the class, then assign this material to output stream

(2.2) for this class and smaller classes, calculate the mass breakage from P, the fraction of material of size less than x produced by breakage of particles of size y

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

and multiply by the mass in the classes, then assign masses to output stream

(2.3) increase size class by 1 and return to 2.1

(3) exit model with stream array completed.

The model is suitable for use where the feed rate is within the manufacturers' specifications:

Symons 7ft crusher: 330-1250 tph -460mm feed
Symons 10ft crusher: 400-1400 tph -660mm feed
Shorthead 7ft crusher: 109-500 tph -210mm feed.

The model does not take into account variation in feed rate, although it has been stated that the parameter K is weakly dependent on feed rate, which is not known *a priori*. This dependence was thought small enough to be neglected. It is left to the user to enter a value of K corresponding to the input CSS. The user should also check the output of the simulator to confirm that the flow rate through the crusher is within design specification.

4.2.3 Gyradisc model

An empirical model for crushing in a gyradisc crusher was developed largely from manufacturers' data, with consideration of the theory of crushing.

Material fed to a gyradisc crusher is distributed around the crushing

chamber where it undergoes interparticle comminution, and is moved towards the discharge by the rotation of the crusher spindle. As the liners are set at an angle less than the angle of repose of the material, it is this motion which determines the residence time of material in the crusher. Particles within the crusher can undergo interparticle comminution in two ways. They can be compressed by other particles and undergo compressive breakage, or they can be abraded by friction as other particles move relative to them.

Since a gyradisc crusher is used for fine material, it is expected that the approximation to the Griffith crack theory for fine particles (29) will be valid. This approximate theory states that the size distribution of fracture products resulting from each fracture mechanism can be expressed by a Rosin-Rammler equation. Since we have two fracture mechanisms, we anticipate two Rosin-Rammler distributions. A similar argument was used for larger crushers where the two fracture mechanisms were compressive and tensile breakage.

Product size distributions obtained from the Gyradisc Crusher Manual (39) for a variety of crushing applications were plotted on RR plots and two distributions were indeed found, one for finer material and a steeper one for coarser material. Figures 15 and 16 are examples of two such plots, one for crushing trap rock, also a hard material, and the other for crushing haematite.

Since particles larger than the CSS will undergo compressive failure, we hypothesise that the upper distribution represents the products formed from compressive failure and that the lower distribution represents those formed by abrasion.

It is known that the product from a gyradisc crusher coarsens with increasing CSS. The dependence of the product size distribution was assumed to be linear. For this reason the particle size used in figure 16 has been non-dimensionalised using the CSS.

From figure 16, the product size distribution can be characterised from the slopes and intercepts of the two RR plots.

The fine distribution has a (non-dimensional) reference size, k, of 250 and an exponent, n, of 0,32 whereas the coarse distribution has a reference size, k, of 0,38 and an exponent, n, of 2,77. The two

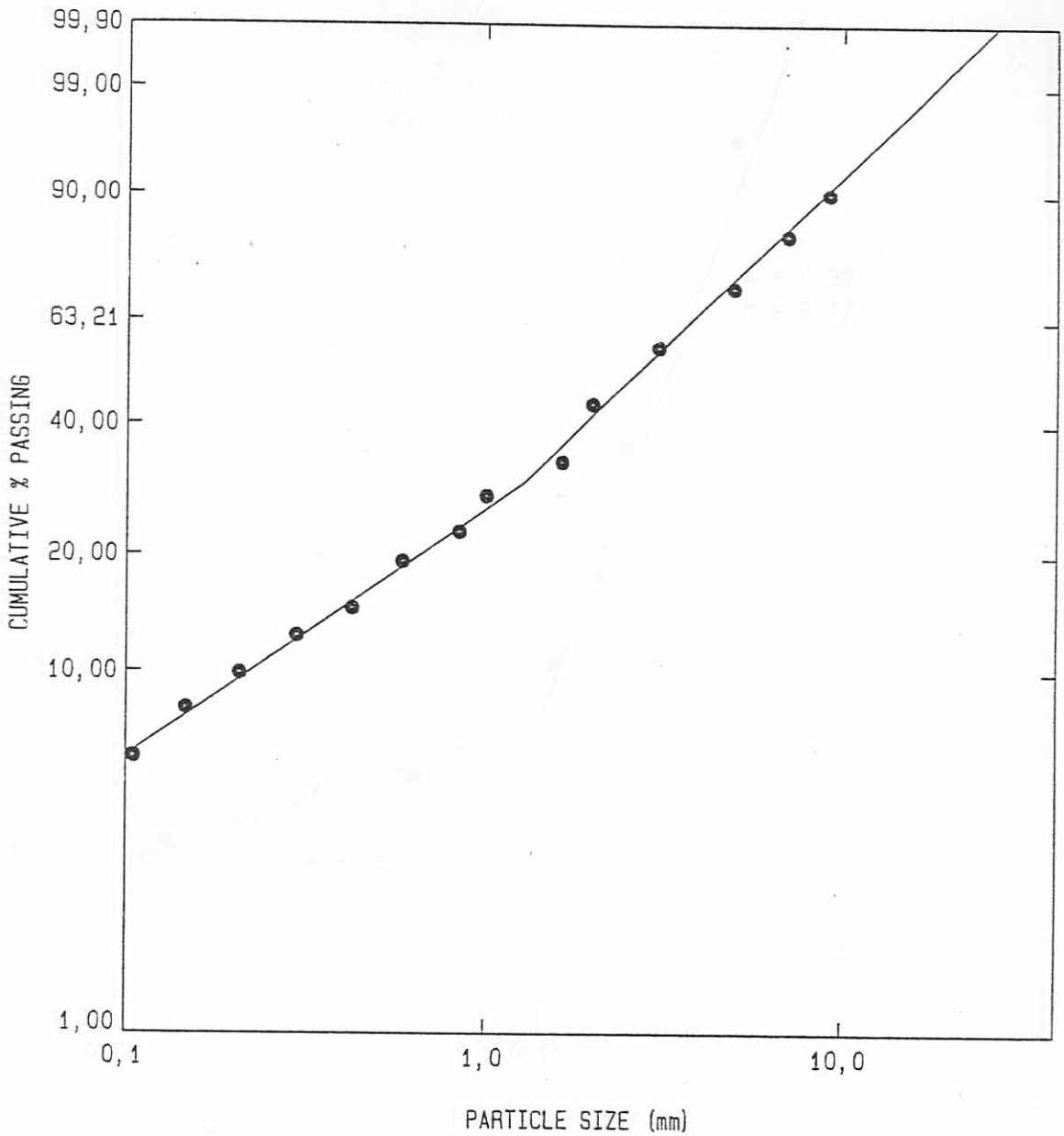


Fig 15 Rosin-Rammler plot for output from gyradisc crushing trap rock

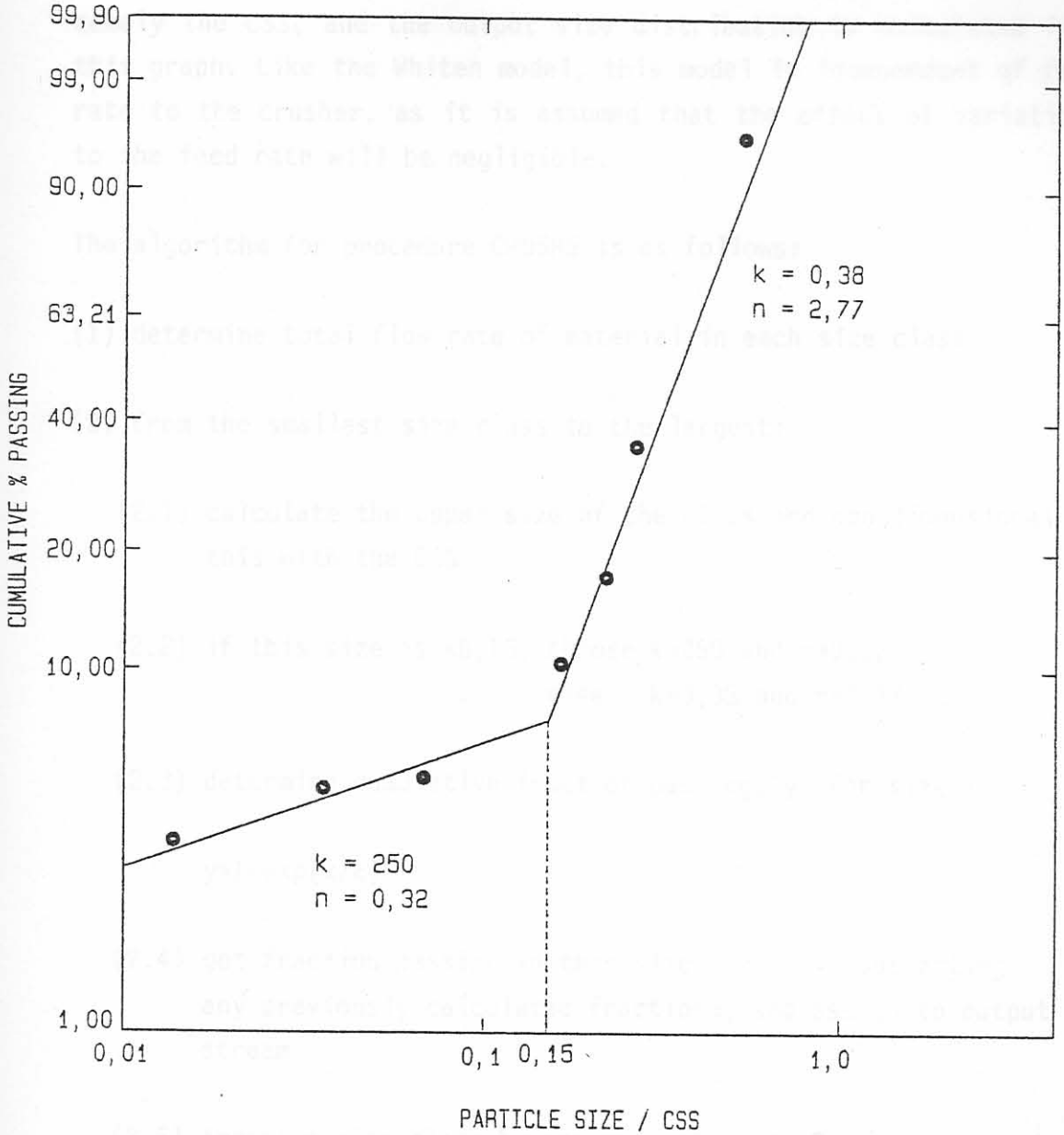


Fig 16 Rosin-Rammler plot for output from gyradisc crushing iron ore

distributions intersect at a non-dimensional particle size of 0,15.

This graph gives an output size distribution dependent only on CSS. Therefore the computer model was written with only one parameter, namely the CSS, and the output size distribution is calculated from this graph. Like the Whiten model, this model is independent of feed rate to the crusher, as it is assumed that the effect of variations to the feed rate will be negligible.

The algorithm for procedure CRUSH5 is as follows:

(1) determine total flow rate of material in each size class

(2) from the smallest size class to the largest:

(2.1) calculate the upper size of the class and non-dimensionalise this with the CSS

(2.2) if this size is <0,15, choose k=250 and n=0,32
else k=0,38 and n=2,77

(2.3) determine cumulative fraction passing, y, for size x

$$y=1-\exp(x/k)^n$$

(2.4) get fraction passing in this size class by subtracting any previously calculated fractions, and assign to output stream

(2.5) increase size class by one and return to 2.1.

(3) exit the model with stream array complete

The model is only valid for flow rates within the maufacturers' specified capacity of 250-300tph of -38mm material. The top size of the feed should be greater that four-fifths of the CSS. This model should not be used to predict the product size distribution of a crusher that is choke fed as this could entrap particles and lead to a greater fraction of fine material being produced.

4.3 Screening models

4.3.1 Enhanced Karra model

The Karra model, the theory of which was given in section 3.4, was modified to take into account the effect of poly decks and of non-square apertures in the following way.

If a poly deck is used, the effective screen area is less than that of an equivalent wire deck. From poly decks presently used on the plant, the average reduction was determined to be 15%. This is also the value used in the empirical Ateliers Bergeaud Macon model, which was supplied by Nordberg (38).

A shape factor was used to account for the non-square aperture effect on screening efficiency. The value of the shape factor, H, for aperture length, l, and width, w, was obtained from Kelly & Spottiswood (29) as:

H = 1,0 for l/w ratio up to 2
H = 1,1 for l/w ratio from 2 to 3
H = 1,4 for l/w ratio from 3 to 6
H = 1,6 for l/w ratio above 6

The model requires six parameters for single deck screening, and ten parameters for double deck screening:

total screen area
angle of inclination of the screen
aperture width, top deck
aperture length, top deck
wire (or poly) thickness, top deck
poly or wire, top deck
aperture width, bottom deck
aperture length, bottom deck
wire (or poly) thickness, bottom deck
poly or wire, bottom deck.

The algorithm for the procedure SCREEN5 is as follows:

(1) from input data determine the empirical coefficients A to H:
(the correlations for these factors are given in Appendix 2)

A=basic capacity factor

B=percentage oversize in feed factor

C=percentage halfsize in feed factor

D=deck location factor

E=wet screening factor

F=bulk density of material

G=reduced area coefficient (1/1,15 for poly deck)

H=shape factor (given above)

and calculate theoretical undersize flow rate (T), screen area (S) and % near size in feed (L)

(2) calculate Z=T/S/(ABCDEFGH)

(3) calculate efficiency=$0,975Z^{-0,148}(1-L/100)^{0,511}$

(4) calculate d50=efficiency(throughfall aperture)

(5) from the smallest size class to the largest:

(5.1) calculate partition coefficients, c, of each deck at the representative size, x. If this size is greater than the aperture size set the partition coefficient equal to 1

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

(5.2) for top deck apportion the mass in the size class to the over- and underflow according to the partition coefficient

(5.3) using the top deck underflow and the bottom deck partition coefficient, apportion the overflow and underflow of this deck

(5.4) increase the size class by 1 and return to 5.1

(6) exit the procedure with the completed output stream arrays.

This model should only be used within the capacity range 17-53tph per square metre of screen area. It is also limited to screening crushed rock and ores.

4.3.2 Rose efficiency model

The Rose test and model described in section 3.4 determine an equilibrium efficiency for a given screen. This efficiency is determined from the values of the blinding, unblinding and screen passage rates. In the plant the equilibrium efficiencies of various screens are known from operating data gathered in many conditions over the years of operation.

The model was developed using this global equilibrium efficiency as one parameter, the other parameter being the screen size at which this efficiency was obtained. This efficiency is then used to calculate d50, equal to the undersize efficiency multiplied by the throughfall aperture. This is identical to Karra's method of calculating the d50 once a screening efficiency is known and is a very good approximation when efficiencies are between 0,7 and 0,95. All efficiencies recorded for the plant are within this range.

Once the d50 has been calculated, the partition curve of the form recommended by Ford (16) and used by Karra (see section 3.4) was used to determine the size distributions in the product streams.

This model has separate versions for both single deck and double deck screening, incorporated in the Microsim library as overlay procedures ROSE1 and ROSE2 respectively.

The model has the following parameters:

screen aperture for top deck on which efficiency is based
efficiency for top deck
screen aperture for bottom deck on which efficiency is based
efficiency for bottom deck

The algorithm for double deck screening is as follows:

(1) calculate the d50 of each deck from the respective screen apertures and the efficiencies

(2) from the smallest size class to the largest:

(2.1) calculate the partition coefficients, c, of each deck at the representative size, x. If this size is greater than the

aperture size set the partition coefficient equal to 1

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

(2.2) for the top deck apportion the mass in the size class to the over- and underflow according to the partition coefficient

(2.3) using the top deck underflow and the bottom deck partition coefficient, apportion the overflow and underflow of this deck

(2.4) increase the size class by 1 and return to 2.1

(3) exit the procedure with the completed output stream arrays.

This model does not incorporate the effect of variations in the feed rate to the screen. Variations in feed rate alter the vibration characteristics of the screen and the bed depth by altering the load on the screen. The change in bed depth will alter the segregation of particles on the screen. It is thus difficult to quantify the effect of variations in feed rate. A rule of thumb exists (29) that states that the screening efficiency varies linearly with feed rate. If an efficiency of 80% represents 100% feed rate, efficiency will decrease by a quarter of a percent for each percent increase in feed up to 140%, and will increase by a quarter of a percent for each percent decrease in feed below 100%, down to about 60%.

It is the responsibility of the user to check the feed rate to the screen after a simulation and to modify the screening efficiency if the flow rate deviates markedly from the rate at which the efficiency was determined. It is expected from the user to ascertain that the feed size distribution does not cause screening efficiencies to change significantly.

5 MODEL VALIDATION AND DISCUSSION

In this chapter, models are tested individually against each other and experimental data. In chapter 6 on plant simulation, models are used in various combinations and at various operating conditions, and compared with plant data.

5.1 Crushing models

The crushing models were tested using a very simple flowsheet in Microsim as given in figure 17.

5.1.1 Whiten model

Whiten's model has been improved to include the correct parameters for the iron ore and the number of breakage events occurring in the crushers on this plant. This is a more appropriate version of the original model in the Microsim unit model library for this application. For use on other plants it will have to be modified again to include the relevant parameters for that plant.

The model caters for both standard Symons cone crushers, as used on the plant for secondary and tertiary crushing, and shorthead crushers, as used in the quaternary plant.

The model was tested for Symons crushers using data collected from the tertiary crusher, operating at a flow rate of approximately 600tph. The CSS was 50mm, and the values of K and IWI required by the model were taken as 0,2 and 26,4kWh/t. Figure 18 gives the output size distribution of the Whiten model, together with experimental values and that of the Nordberg model in the Microsim unit library.

It can be seen that the Whiten model gives a more accurate output size distribution than does the Nordberg model, and that the Whiten model agrees closely with experimental values.

For shorthead crushers, the model was tested using data collected from the fresh feed crusher of the quaternary plant. The CSS was 25mm, and feed rate 520tph and the values of K and IWI were taken as 0,2 and 26,4kWh/t respectively. Figure 19 gives the output size distribution predicted by the Whiten model for a shorthead crusher

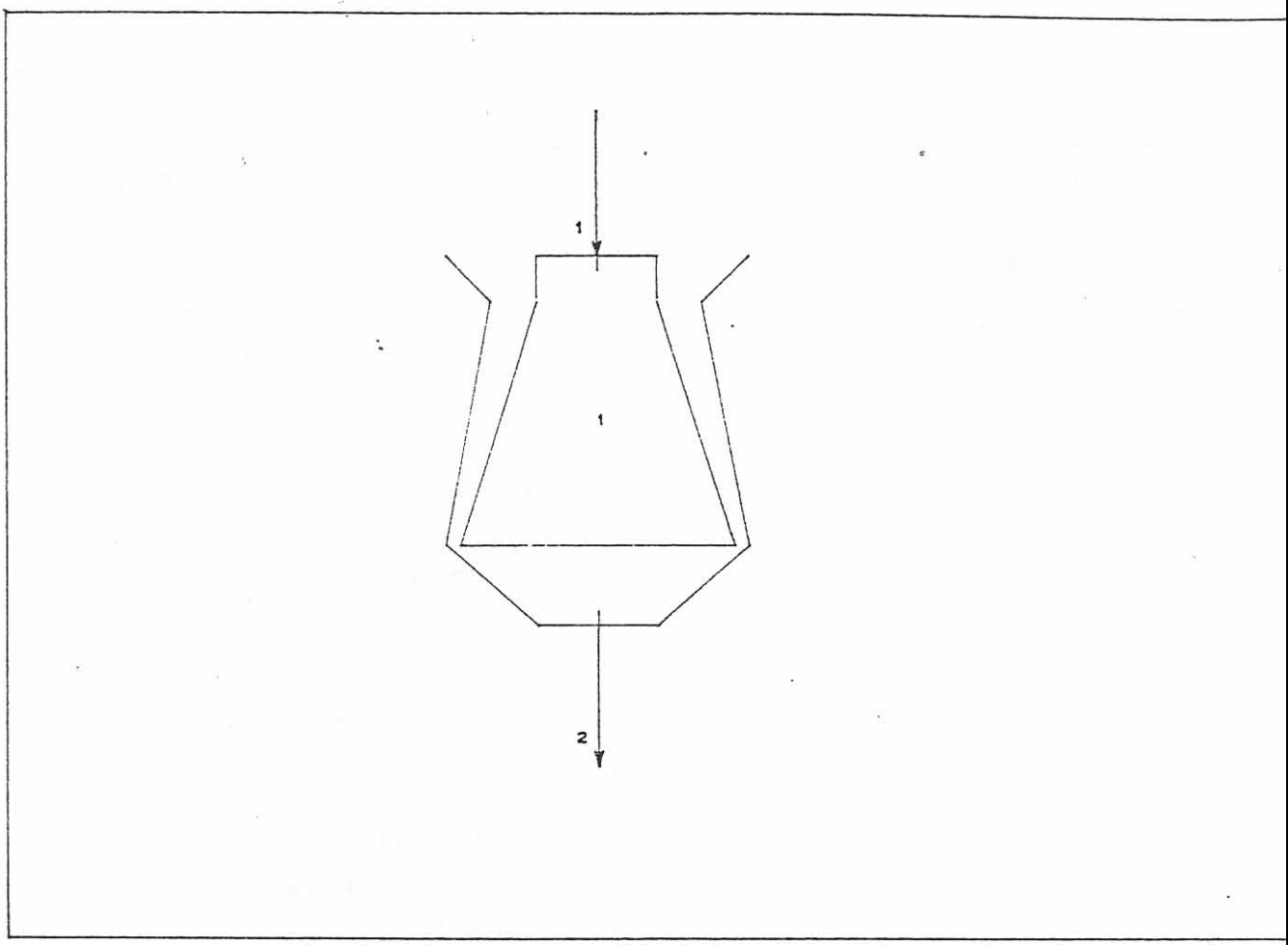


Fig 17 Flowsheet for testing crusher models

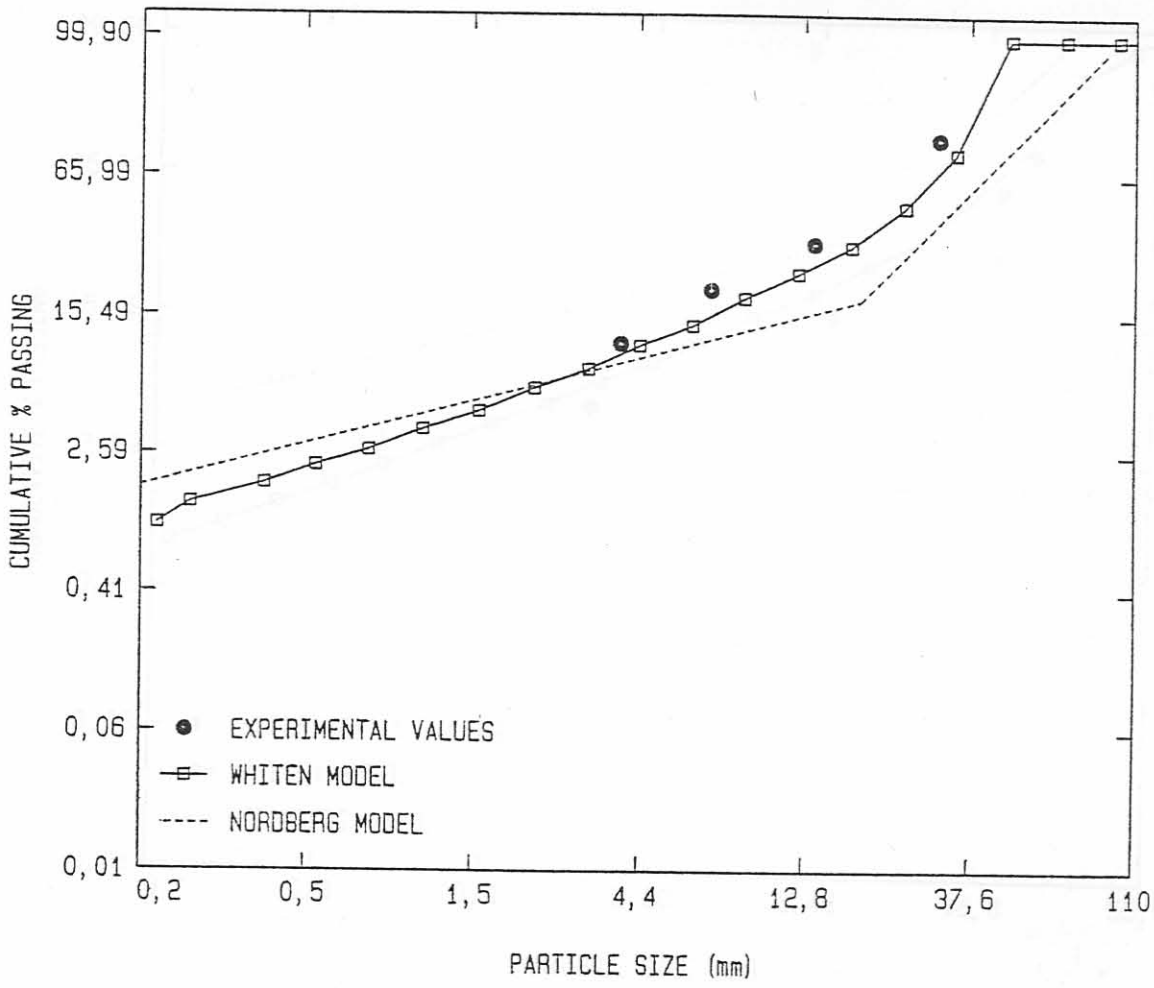


Fig 18 Rosin-Rammler plot for Whiten and Nordberg models output with closed side setting of 50mm, and experimental values

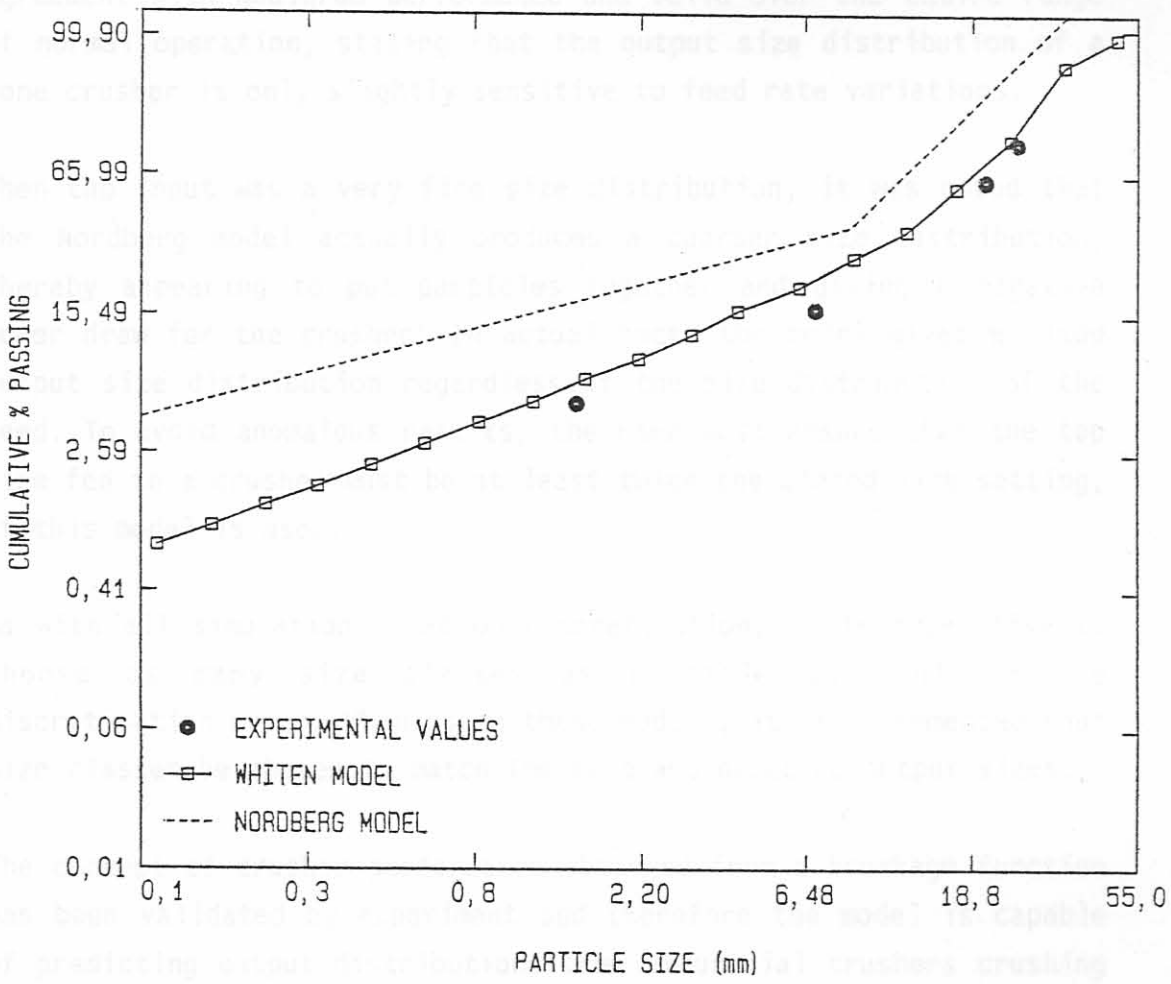


Fig 19 Rosin-Rammler plot for Whiten and Nordberg models output with closed side setting of 25mm, and experimental values

for a closed side setting of 25mm, together with experimental values and values predicted by the Nordberg model.

The Whiten model again gives a more accurate prediction than the Nordberg model and agrees closely with experimental values.

Whiten (57) has also used this model with the parameters as specified for haematite (and incorporated in the new model) on an Australian crushing application and found it to be in excellent agreement with measured performance and valid over the entire range of normal operation, stating that the output size distribution of a cone crusher is only slightly sensitive to feed rate variations.

When the input was a very fine size distribution, it was noted that the Nordberg model actually produces a coarser size distribution, thereby appearing to put particles together and giving a negative power draw for the crusher! In actual fact, the model gives a fixed output size distribution regardless of the size distribution of the feed. To avoid anomalous results, the user must ensure that the top size fed to a crusher must be at least twice the closed side setting, if this model is used.

As with all simulation based on discretisation, it is imperative to choose as many size classes as possible to minimise the discretisation error. When using these models, it is recommended that size classes be chosen to match the feed and expected output sizes.

The concept of crusher performance obtained from a breakage function has been validated by experiment and therefore the model is capable of predicting output distributions from industrial crushers crushing haemetite. For greater accuracy the dependence of K, the proportion of fines produced during breakage events, on the CSS, should be experimentally established.

5.1.2 Gyradisc model

This new gyradisc model was tested against data obtained from separate test runs on the gyradisc crusher of the quaternary plant.

For various values of closed side setting (the dependent variable in the gyradisc model), feed and product size distributions were determined by screen analysis of a belt cut. From the given input size distributions the model was run and the product size distributions were compared with those determined by screening analysis. Figures 20 to 23 give these comparisons with experimental values.

For figure 20, CSS=20mm, feed rate = 200tph
figure 21, CSS=17mm, feed rate = 280tph
figure 22, CSS=14mm, feed rate = 210tph
figure 23, CSS=13mm, feed rate = 350tph.

The gryadisc model shows very good agreement with experimentally measured data for a variety of closed side settings. The measurements were taken over a wide range of flow rates (even outside the manufacturers' specifications of 250-300tph) and the results appear to be insensitive to a change in flowrate.

Thus the gyradisc model very accurately predicts the product size distribution from the crusher and validates the use of CSS as the only model parameter. The model can also be used for a wider range of feed rates than the manufacturers specify.

This model can be used for closed side settings of up to 25mm, and the feed must be -38mm, with a top size of above 0,8CSS.

It is expected that the parameters of the fine and coarse size distributions will vary according to ore type. The model is therefore only valid for haemetite.

Again, the size classes used with the model should be chosen to give best results by having the greatest number of size classes possible, and choosing size classes to match feed and expected output size distribution.

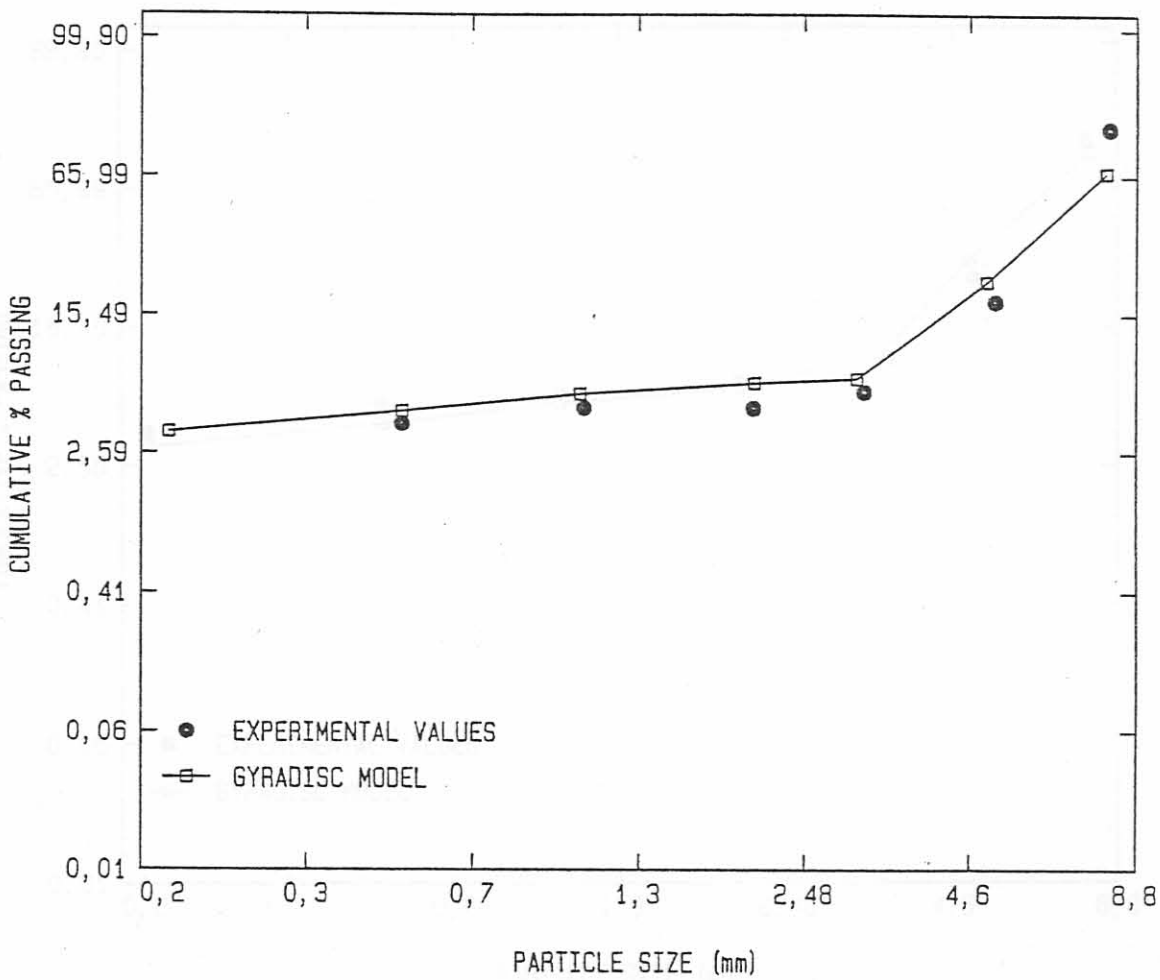


Fig 20 Rosin-Rammler plot for Gyradisc model output with closed side setting of 20mm, and experimental values

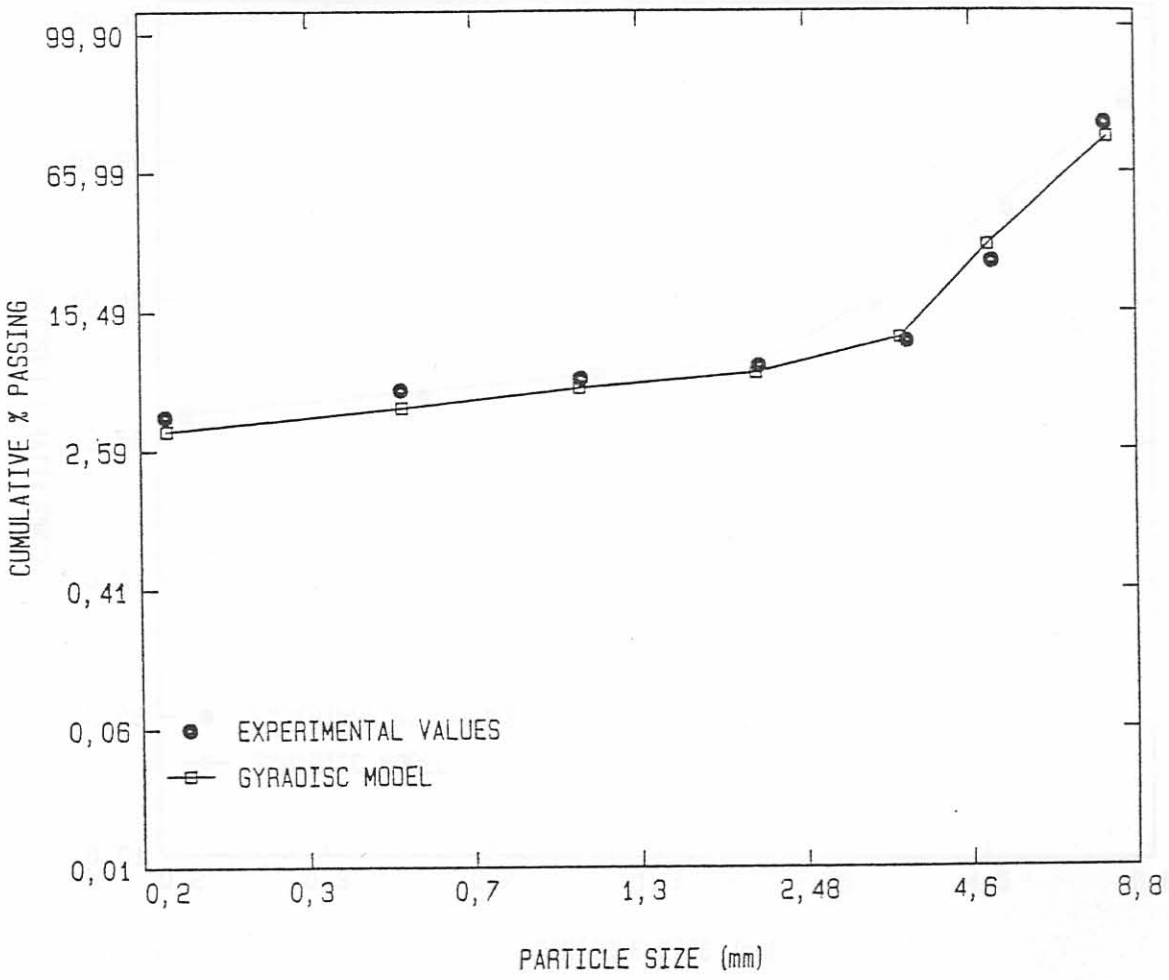


Fig 21 Rosin-Rammler plot for Gyradisc model output with closed side setting of 17mm, and experimental values

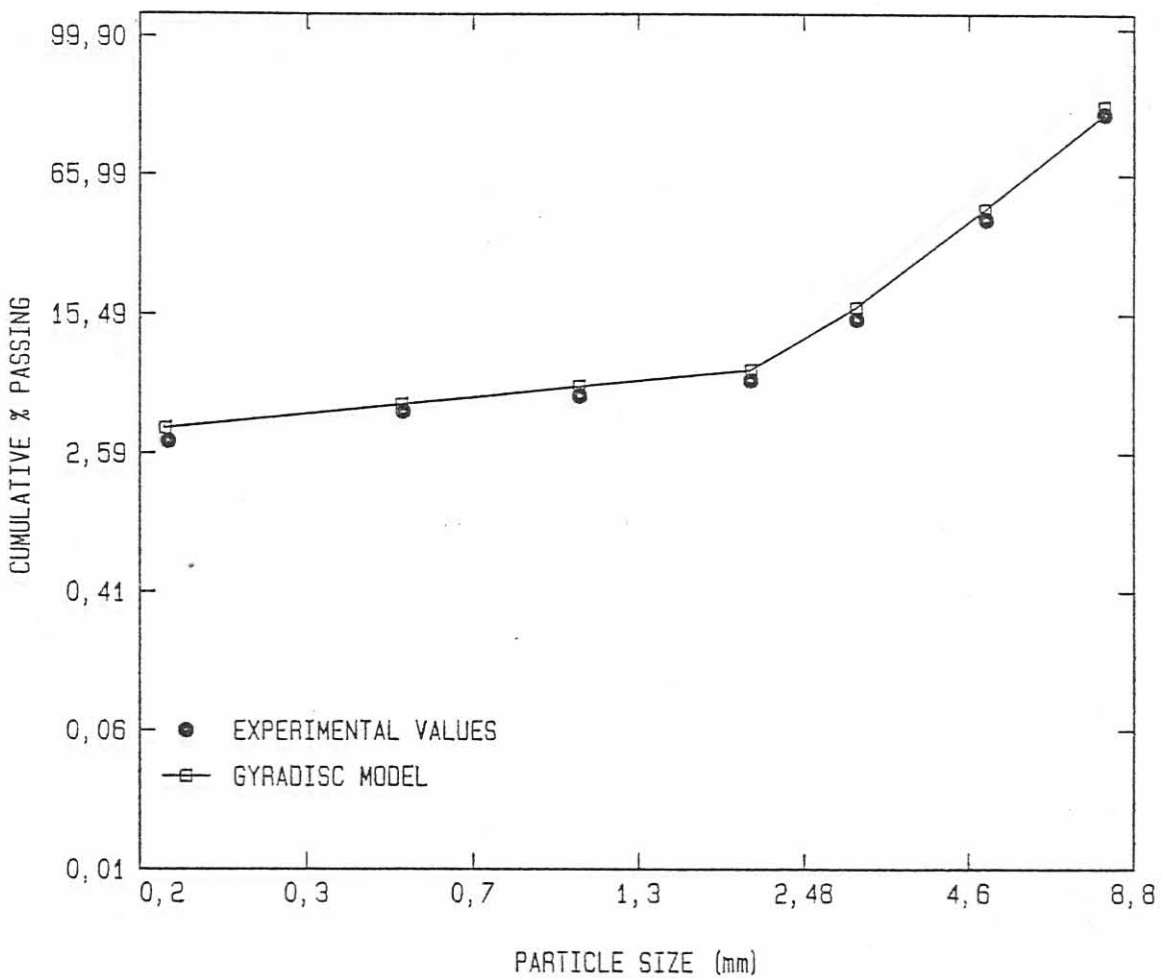


Fig 22 Rosin-Rammler plot for Gyradisc model output with closed side setting of 14mm, and experimental values

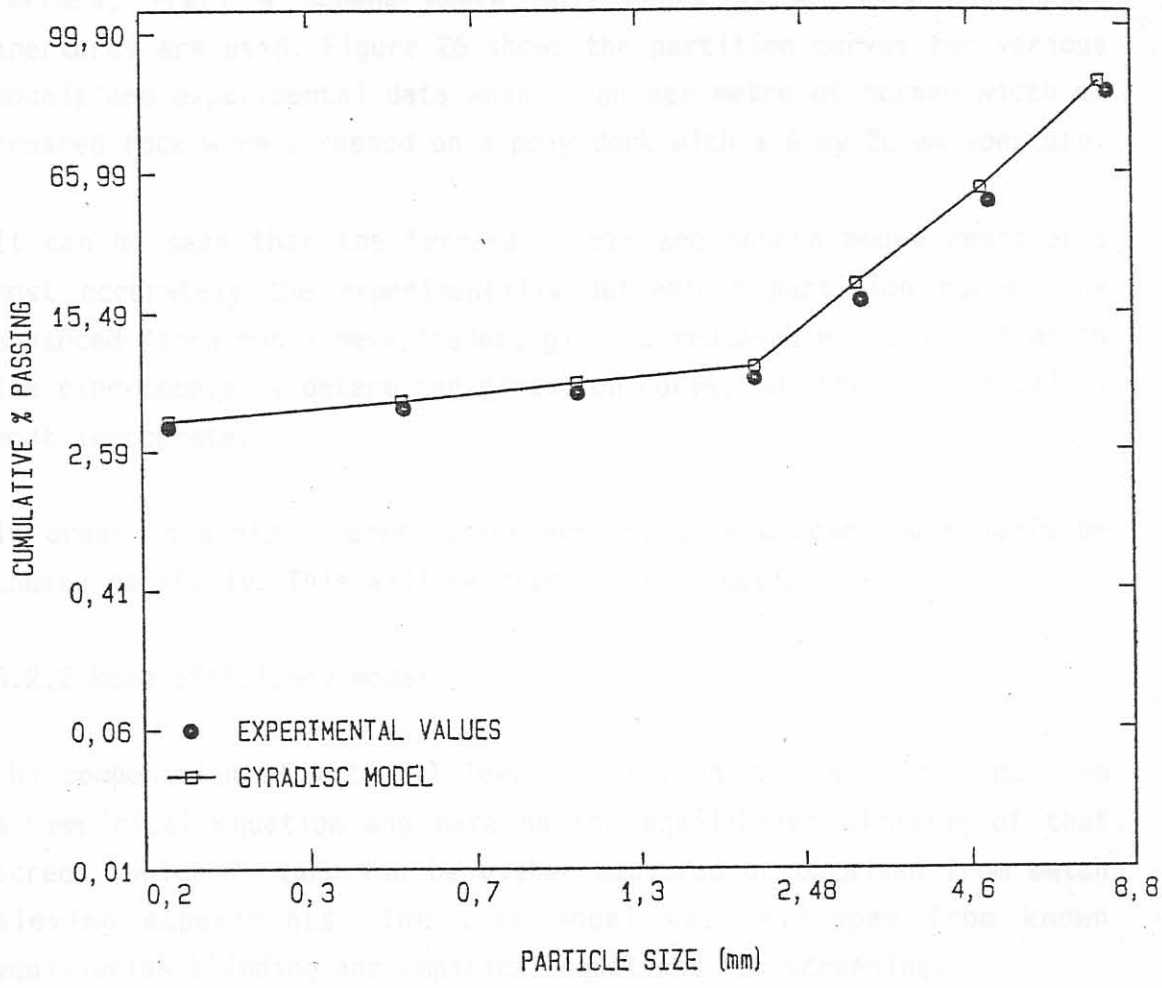


Fig 23 Rosin-Rammler plot for Gyradisc model output with closed side setting of 13mm, and experimental values

5.2 Screening models

Screening models were tested using the flow diagrams shown in figures 24 and 25.

5.2.1 Enhanced Karra model

This model was tested on a single deck using the test data of Ferrara, Preti & Schena (13) in order to compare the model to that of Ferrara, Preti & Schena where poly decks as well as non-square apertures are used. Figure 26 shows the partition curves for various models and experimental data when 71tph per metre of screen width of crushed rock were screened on a poly deck with a 6 by 20 mm aperture.

It can be seen that the Ferrara, Preti and Schena model represents most accurately the experimentally determined partition curve. The enhanced Karra model nevertheless gives a reasonable approximation to the experimentally determined partition curve, but the ideal model is most inaccurate.

In order to avoid discretisation errors, size classes must again be chosen carefully. This will be discussed in section 5.3.

5.2.2 Rose efficiency model

The composition of material leaving a screen can be calculated from an empirical equation and data on the equilibrium blinding of that screen, which in turn can be either measured or obtained from batch sieving experiments. The Rose model was developed from known equilibrium blinding and empirical equations for screening.

The single deck Rose model was tested against the Ferrara, Preti & Schena model and experimental data for a single screen with 4mm square apertures and at a feed rate of 60tph per metre of screen width and the partition curves are shown in figure 27, together with experimental values and the partition curve given by the ideal model.

It can be seen that the Rose efficiency model is almost as accurate as the Ferrara, Preti and Schena model in representing the experimentally determined partition curve, but that the ideal model is most inaccurate.

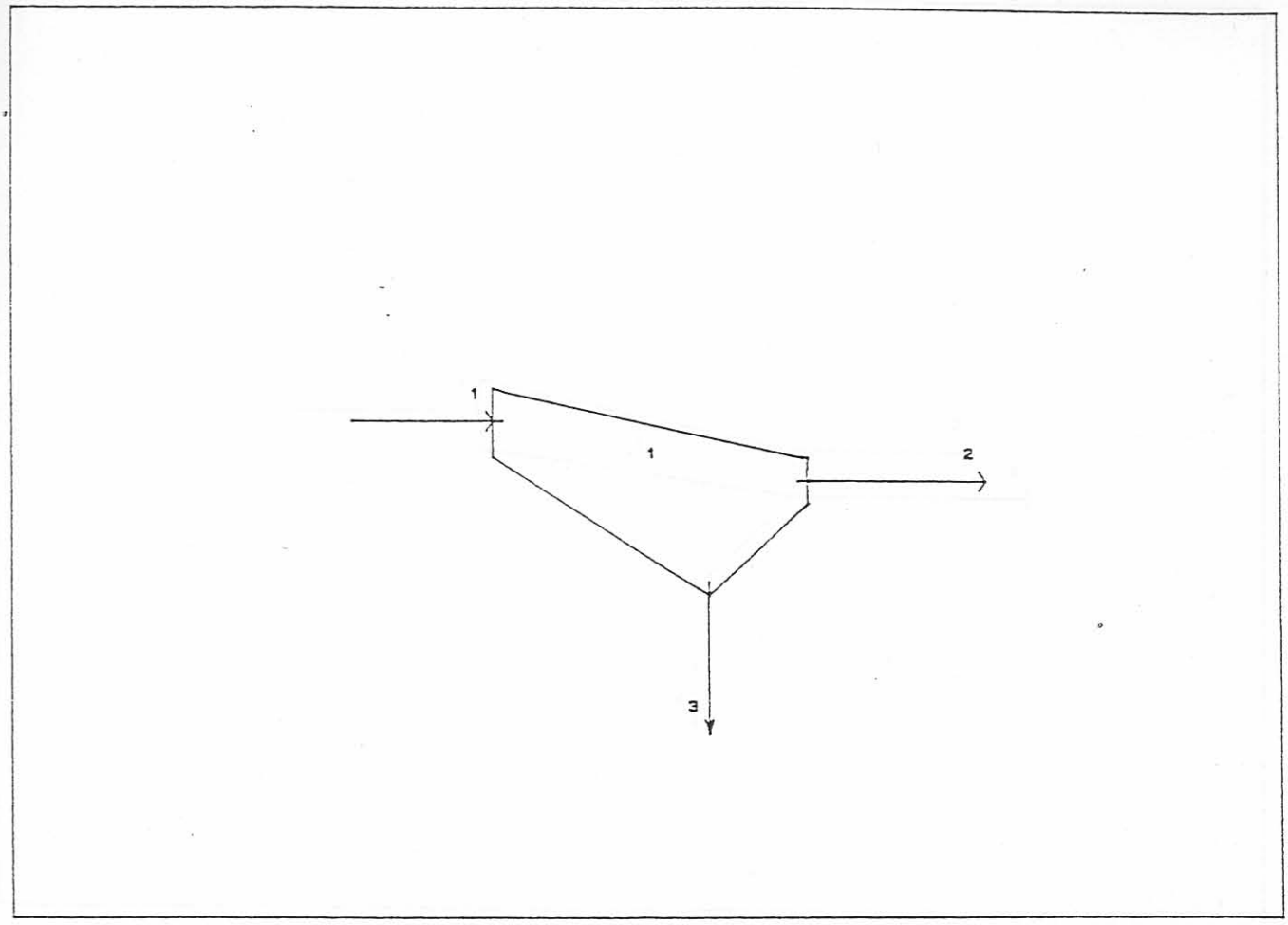


Fig 24 Flowsheet for testing single deck screen models

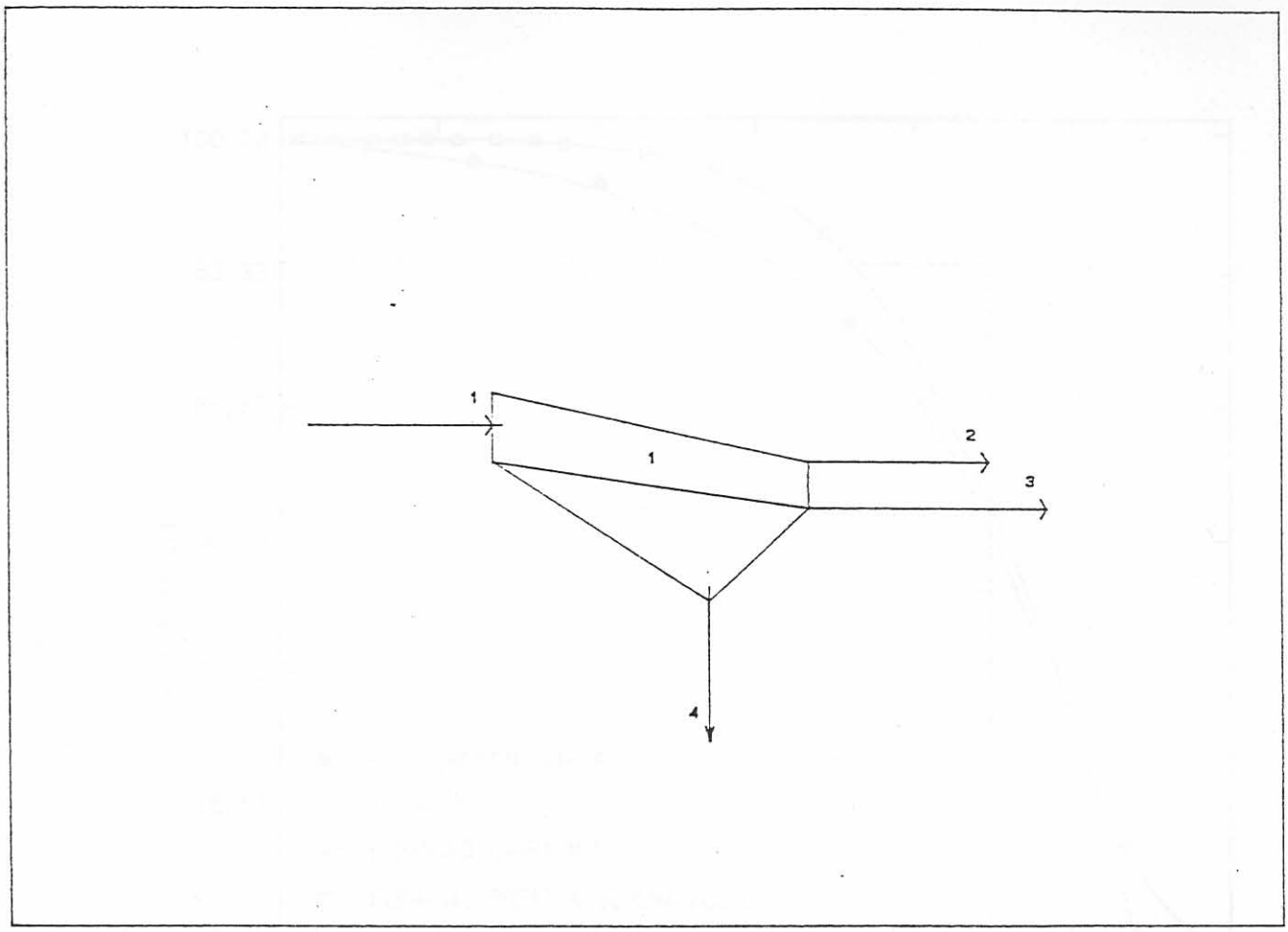


Fig 25 Flowsheet for testing double deck screen models

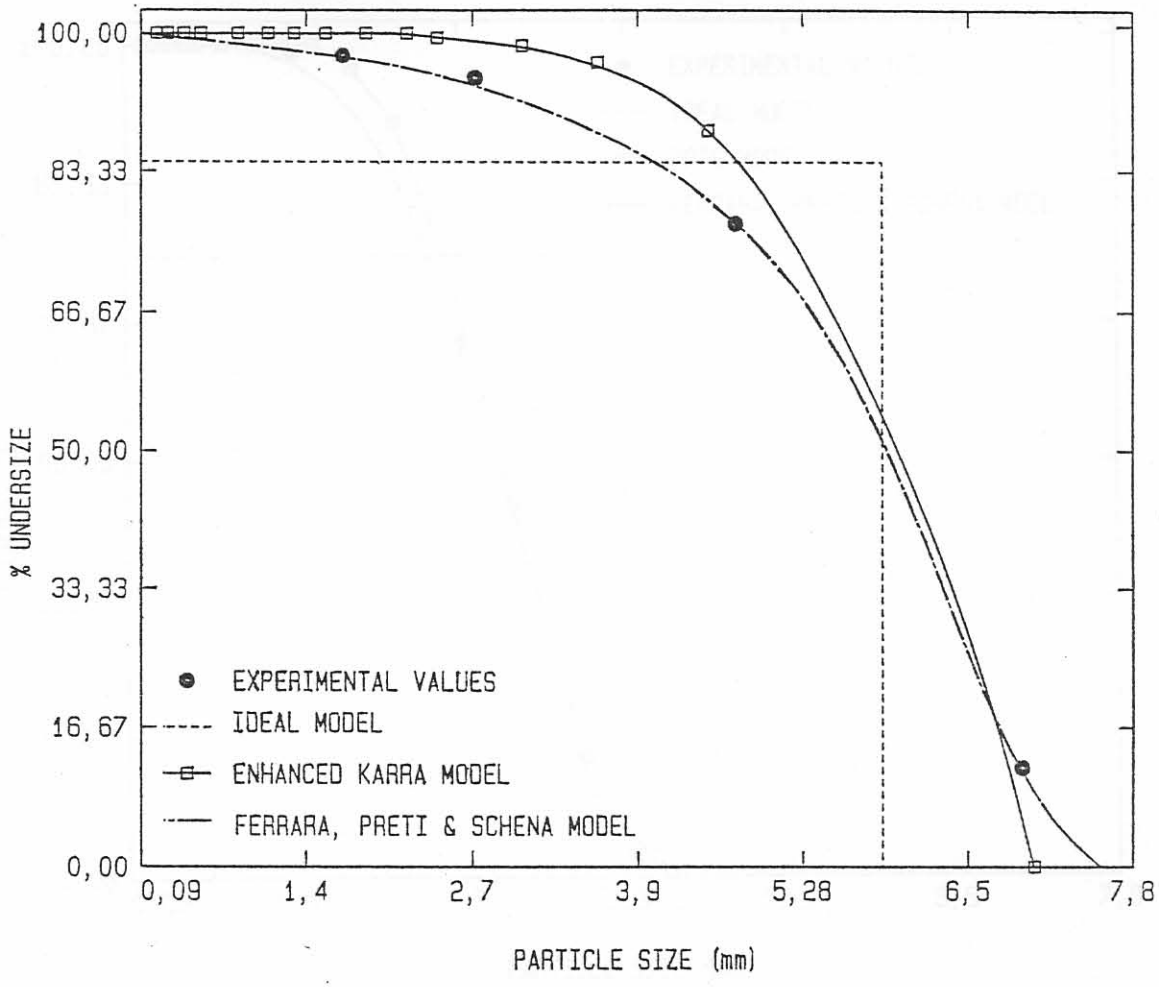


Fig 26 Partition curves for enhanced Karra & other models and experimental values, all for a single deck screen

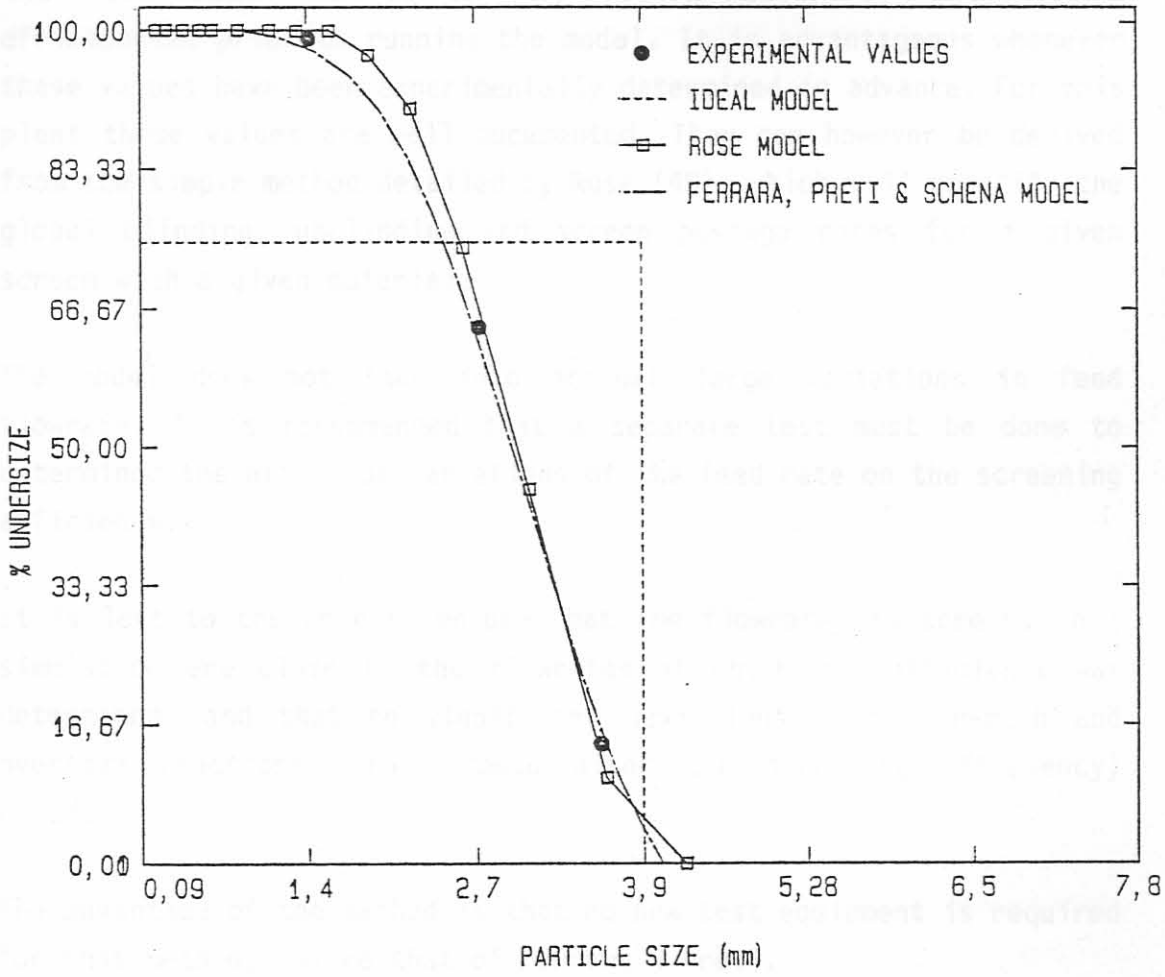


Fig 27 Partition curves for Rose and other models and experimental values, all for a single deck screen

By comparing figures 26 and 27 it can be seen that the Rose model gives better relative accuracy than the enhanced Karra model. This is not surprising as the enhanced Karra model relies entirely on empirically derived equations rather than measured values. The enhanced Karra model, however, can be used with no operating data. It is valid for most industrial processes and is thus completely transferable to other plants, where different screens are used and different materials screened.

The Rose model relies on the determination of equilibrium efficiencies prior to running the model. It is advantageous whenever these values have been experimentally determined in advance. For this plant these values are well documented. They can however be derived from the simple method detailed by Rose (49), which will quantify the global blinding, unblinding and screen passage rates for a given screen with a given material.

The model does not take into account large variations in feed flowrate. It is recommended that a separate test must be done to determined the effect of variations of the feed rate on the screening efficiency.

It is left to the user to ensure that the flowrates to screens in a simulation are close to the flowrates at which the efficiency was determined, and that no significant deviations from near-mesh and oversize fractions (which could alter the screening efficiency) occur.

The advantage of the method is that no new test equipment is required for this method, unlike that of Ferrara & Preti.

The model of Ferrara & Preti (13) uses the half-size mass velocity, k50 (described in section 3.4.3), to define the screening process by, effectively, one parameter for a given type of screen. This value is a strong function of aperture size, characteristics of the screening surface, vibration characteristics and inclination of the screen. As this model is the most accurate model, it would be helpful to build an empirical model around values of this parameter as specified by a given screen.

Sullivan's screenability characteristics method (52) can be used to

apply this model to the screening of a new material with the same type of screens by determining a percentage change in screening efficiency. The Rose model can thus be used in a wide variety of plants and can even be used by a designer who has access to screening efficiency data of a manufacturer's screen and knows the screenability characteristics of his ore, to predict screening performance accurately. It is thus transferable to other plants.

5.3 Microsim and model accuracy

In this chapter, the flowsheets used for model validation (figures 17, 24 and 25) contain only one unit each. It is thus easy to choose size classes to fit the unit and to use the maximum number of size classes corresponding to the input experimental data, or the maximum number of size classes permitted by the simulator. This was set at 40 for Microsim, but Version 3.0 was restricted to 20 for use on a 640kB microcomputer. The user may change this by editing the file TYPEDEF.PAS and recompliling the program.

The greater the number of size classes used, the better the discretisation of continuous functions by Microsim. It has been found that using too few size classes can sometimes lead to anomalous results.

For crushing applications, the effect of number of size classes is small, with more classes giving better approximations.

However, for screening applications, the choice of size classes is of utmost importance. To avoid anomalous results size classes should correspond to screen dimensions as closely as possible. This ensures that the representative size of the class is always on the same side of the screen aperture as the top size of the class.

When a partition curve is used there is another reason for choosing size classes carefully. The partition curve used by both the Karra and the Rose models is a steep function of size below mesh size, hence requiring small size classes to represent it accurately.

As an example, consider the double deck screen used for testing the screen models. Assume a user wished to ascertain how this double deck screen would perform if the top deck had an 8mm aperture size and the

bottom deck a 5mm aperture size. However, the user has done a screen analysis of the feed stream and obtained the following input size classes: +10mm, -10/+5mm, -5/+3mm, -3/+2mm, -2mm, as these coincide with his laboratory equipment.

All the +10mm material will be assigned to the overflow of the top deck, as expected. However, the next size class has a representative size of 7,1mm, which is close to the screen aperture size. The partition coefficient corresponding to this representative size is close to unity (closer if the screening efficiency is low). This results in almost the entire -10/+5mm stream being assigned to the overflow of the top deck! The smaller fractions have low partition coefficients and hence pass almost completely to the second deck. Coefficients for the lower deck can then be calculated, whence a small amount of the -5/+3mm will be assigned to the overflow for the lower deck.

The simulator thus has assigned to the overflow of the bottom deck almost no material, with none of it in the -8/+5mm fraction.

When a far larger number of size classes were used, the overflow of the bottom deck contained more -8/+5mm particles, indicating that the error was due to the number of size classes chosen.

Size classes must be chosen with extreme care and with due consideration for the unit parameters in the flowsheet. If a flowsheet contains a large number of units, with a broad range of particle sizes being processed, it might be preferable to use the ideal screen model. This model has a step partition curve which is thus discretised without error. It is still useful to choose size classes with top sizes corresponding to screen apertures.

If Microsim is used to optimise screen apertures, of necessity, size classes cannot be chosen to coincide with screen apertures for each iteration of the optimisation routine. This can lead to anomalous results.

The question arises as to if and how one can extend limited experimental data to incorporate more size classes, i.e. how material in a large size class can be apportioned to a greater number of narrower size classes covering the original range. It was felt

that the best way of accomplishing this was to plot the few experimental points on various axes to establish whether the data might fit a known size distribution (e.g. the Rosin-Rammler, Broadbent-Callcott, Gaudin-Melloy or Schumann). If so, then the appropriate distribution and its parameters could be entered into Microsim, and the user could then choose size classes to suit the flowsheet.

The above example and the model results illustrate that Microsim can provide accurate simulation of crushing and screening models, but the accuracy depends on the quality of information input to the simulator and the care taken by the user to avoid errors caused by discretisation.

6 PLANT SIMULATION

6.1 Simulation of the quaternary plant

With the updated Microsim unit model library, plant simulation may now be attempted. The plant is divided operationally into the four subsections given in chapter 2 and these subsections are separated by stockpiles. It is the quaternary plant (SP4) which produces more than 50% of the final products and it is in this plant that changes are made to produce either two or three ore products. It is also the only sub-plant in which crushing occurs in steady state. For this reason it was decided to simulate first the quaternary plant (SP4) where a feed size distribution could also be measured. In the simulation study of this sub-plant we examine the proportion of ores produced.

The flowsheet for SP4 is given in figure 7. The following simulation study uses the new Whiten model for the shorthead crushers, the new gyradisc model for the fines crusher and the efficiency model with plant efficiency data throughout. All the relevant information for this plant was entered into Microsim.

A simulation of normal operating conditions was done using as input a measured size distribution and flow rate for streams one and three. The products of such a flowsheet are lumpy ore in stream six and fine ore in stream eight. The size distributions of these product streams are given in figure 28, together with measured values.

From the Microsim mass balance the respective flow rates of fine and lumpy ore were 770tph and 1670tph. The combined feed rate to the sub-plant was 2450tph. The mass balance is thus accurate to within half of a percent. The other source of lumpy ore is the output from the medium drum plant, whereas the output from the fine cyclone plant is also fine ore. If these output values from the medium drum and fine cyclone plants are combined with the simulated output from SP4, the overall production ratio of fine to lumpy ore for the plant is calculated to be 36:64. This is in very good agreement with the recorded ratio of 35:65 obtained during normal operation, hence validating our choice of models.

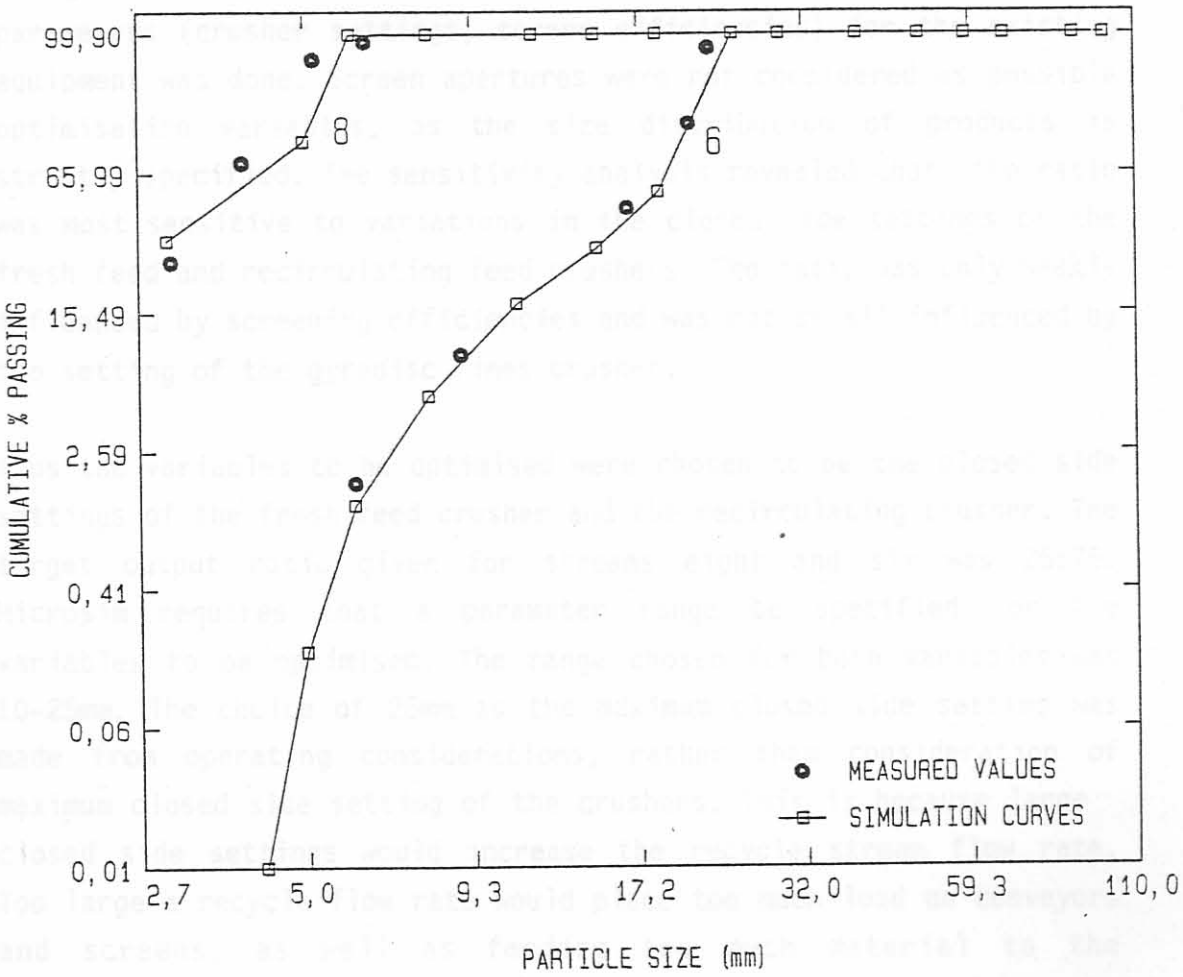


Fig 28 Rosin-Rammler plots for output streams from sub-plant 4 by simulation and measured values

6.2 Optimisation of the lumpy:fine ore ratio

It has been mentioned that the fine to lumpy ore ratio is to be improved (to 25:75 if at all possible), in order to reduce the existing fine ore stockpile. With the optimisation capability of Microsim Version 3.0, studies were done attempting to attain this ratio.

Firstly, using the simulation of the quaternary plant, a sensitivity analysis was performed. A ten percent variation in changeable parameters (crusher settings, screen efficiencies) for the existing equipment was done. Screen apertures were not considered as possible optimisation variables, as the size distribution of products is strictly specified. The sensitivity analysis revealed that the ratio was most sensitive to variations in the closed side settings of the fresh feed and recirculating feed crushers. The ratio was only weakly influenced by screening efficiencies and was not at all influenced by the setting of the gyradisc fines crusher.

Thus the variables to be optimised were chosen to be the closed side settings of the fresh feed crusher and the recirculating crusher. The target output ratio given for streams eight and six was 25:75. Microsim requires that a parameter range be specified for the variables to be optimised. The range chosen for both variables was 10-25mm. The choice of 25mm as the maximum closed side setting was made from operating considerations, rather than consideration of maximum closed side setting of the crushers. This is because large closed side settings would increase the recycle stream flow rate. Too large a recycle flow rate would place too much load on conveyors and screens, as well as feeding too much material to the recirculating feed crusher.

Using these constraints, the optimisation calculations were run using Microsim. It was necessary to change the default step size for the optimum to be reached in 20 optimisation iterations.

The optimum values of the closed side settings were given by Microsim to be 25mm for both the fresh feed crusher and the recirculating crusher. However, the target ratio of fine to lumpy ore was not reached using these settings. The increased flow rates in various streams required that some slight modifications to screening

efficiencies be made by using a rule of thumb method. This did not influence the output flow rates significantly. The final flow rates of fine and lumpy ore respectively were 733tph and 1686tph. This corresponded to a ratio of 34:66 when these streams were combined with the output from the fine cyclone and medium drum plants respectively.

This improvement in ratio is small, indicating that the quaternary plant is presently running at close to the best production ratio possible with the given feed. The improvement in ore ratio should now however be economically evaluated, as the power draw to the crushers and conveyor belts will have changed.

Crushing is obviously the most important operation to determine the ratios of ores produced by the plant. In order to improve the fine to lumpy ore ratio toward the 25:75 target, modifications will have to be made in the primary to tertiary comminution units. This can be done by increasing the size distribution of the input to the quaternary plant or by improving the increasing the amount of material to the medium drum plant and decreasing that to the fine cyclone plant.

6.3 Production of direct reduction ore

When the plant is required to produce direct reduction ore in addition to fine and lumpy ore, a few modifications are made to the flow of material in the plant. The product from the coarse cyclone plant is not fed to the quaternary plant at all (i.e. stream 3 in figure 7 is eliminated). Rather, this fine cyclone plant product is screened at 5mm and the -8/+5mm material is diverted to the direct reduction ore bed with the -5mm fraction going to the fine ore bed. The gyradisc crusher is eliminated from the quaternary plant flowsheet, and the top product of the secondary screens is routed to the direct reduction ore bed. The lower decks of the primary screens are effectively replaced with screens of 11mm aperture, by using an alternate bank of screens fitted with the correct lower decks.

With this new configuration the flow rate to the quaternary plant has been reduced to 2000tph. Simulation of this flowsheet yielded the following production rates of the three ores:

359tph fine ore
468tph direct reduction ore
1166tph lumpy ore.

By combining these flow rates with the flow rate of respective ores from the fine cyclone plant, coarse cyclone plant and medium drum plant, the plant production ratio for the ores is found to be 27:21:52 (fine:direct reduction:lumpy ore). This is compared to the 29:18:53 split obtained in from operating data. Again, Microsim, using the new crushing models and using known screening efficiencies provides an accurate means of simulating this quaternary plant for different products and flow rates.

6.4 Overall plant simulation

The entire plant as given in figures 1 to 7 is sufficiently small to be used as a single flowsheet by Microsim, which has a maximum of 100 for both the total number of units and the total number of streams. However, it is better to keep the sub-plants separate to aid evaluation of results.

It is in the primary to tertiary comminution units of sub-plant 1 that further improvement to the ratio of fine to lumpy ore can be made. However, this sub-plant does not operate in a steady state throughout as the primary gyratory crusher is fed from tip trucks and units downstream experience surges of feed. These surges lessen with distance downstream. Simulation of this sub-plant will now be attempted.

As the size distribution of run-of-mine cannot be determined, the rock fragmentation model given in section 3.5 will be used to estimate this size distribution.

For the blasting procedures used in the iron ore mine a Rosin-Rammler distribution with a representative size of 633mm and an exponent of 0,92 was obtained using this model.

Sub-plant 1 was then simulated using the Nordberg gyratory model for the primary crusher, the modified Whiten model for secondary and tertiary comminution and the ideal screen model for the grizzly feed screens, together with the plant parameters. The input (which represents the rock fragmentation model) and output size distributions are shown in figure 29, together with measured values of the output of sub-plant 1.

The percentage retained at 25mm is 31%, instead of 61% as recorded on plant. This implies that the simulator overestimates the +25mm fraction of the feed to the washing and screening plant by about 50%. Hence the flow rate to the quaternary plant from the medium drum plant will show a similar error. This will give flow rates out of range for simulating the quaternary plant.

The simulated results show an output consistently coarser than that occurring in practice. This unacceptably large error could be due

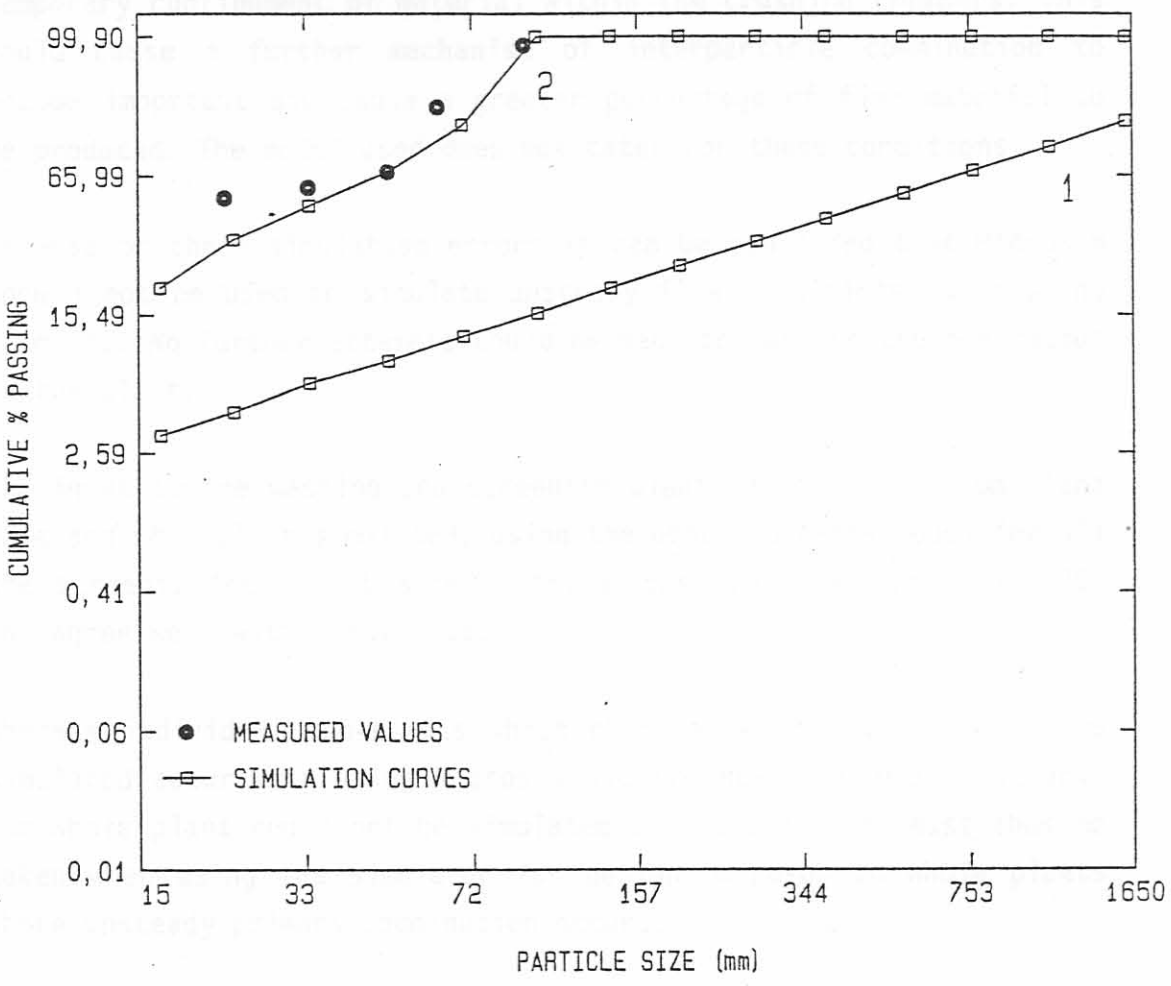


Fig 29 Rosin-Rammler plot of feed and output from sub-plant 1 by simulation, and measured values

either to inaccuracy of the gyratory crusher model, or to the lack of steady state in this sub-plant.

The Nordberg gyratory model used provides a fixed size distribution as output, regardless of input size distribution, and is a general model for any ore. This could provide erroneous results for an ore like haematite.

The surges of feed to the secondary and tertiary crushers could cause temporary confinement of material within the crushing chambers. This could cause a further mechanism of interparticle comminution to become important and cause a greater percentage of fine material to be produced. The model used does not cater for these conditions.

Because of these simulation errors it can be concluded that Microsim should not be used to simulate unsteady flow conditions in crushing circuits. No further attempts could be made to improve the ore ratios in the plant.

The input to the washing and screening plant was obtained from plant data and this plant simulated, using the enhanced Karra model for all the screens. The output size distributions are given in figure 30, and agree well with plant data.

Whereas individual sub-plants which operate in steady state may be simulated accurately using Microsim and the new unit model library, the whole plant could not be simulated accurately. Care must thus be taken when using the simulator for design purposes on whole plants where unsteady primary comminution occurs.

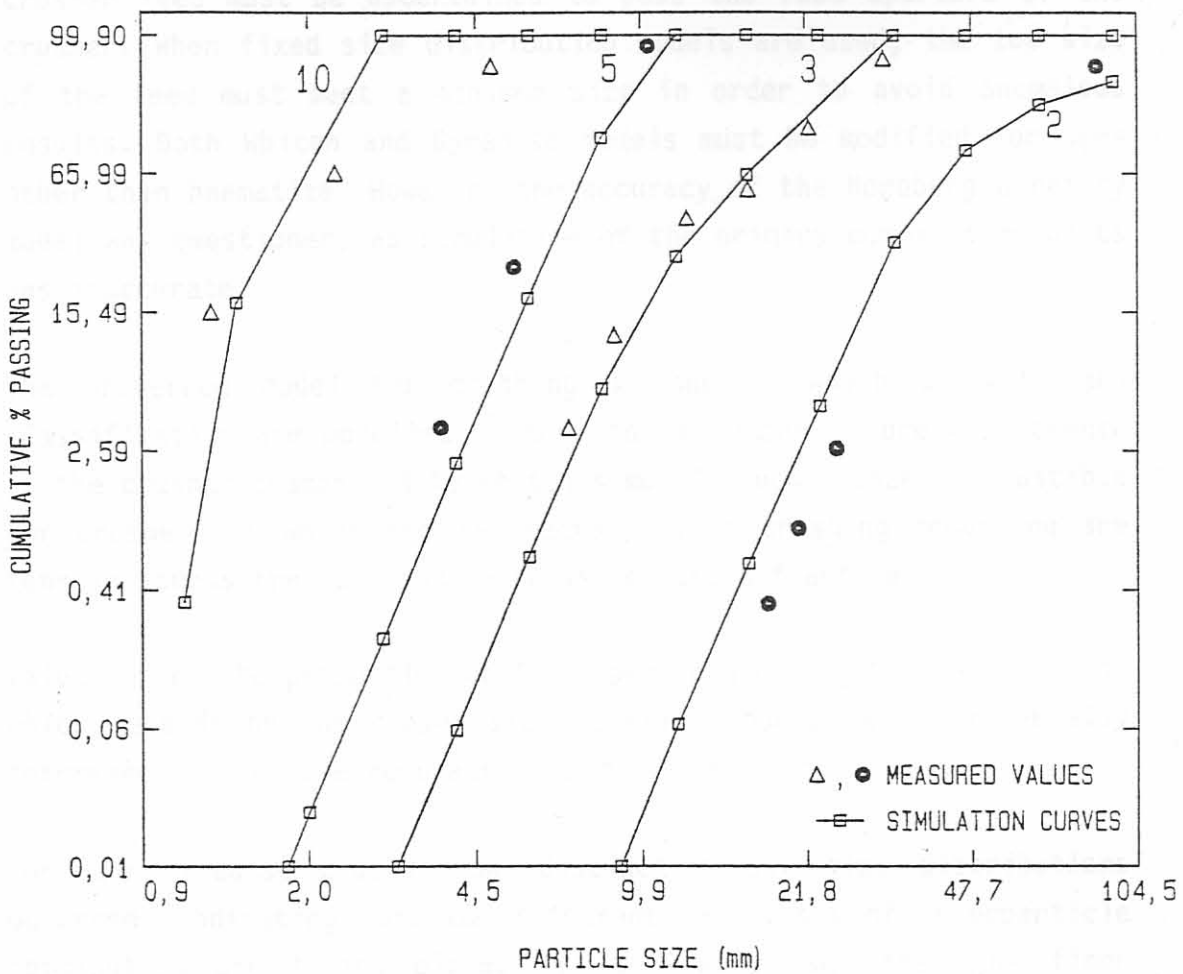


Fig 30 Rosin-Rammler plot of output from sub-plant 2 by simulation, and measured values

7 CONCLUSIONS

7.1 Crushing models

Accurate steady state crushing models have been developed which have applicability to the iron ore beneficiation plant. The models are restricted to design capacity ranges and do not apply to surge-fed or choke-fed crushing applications, where a further mechanism of interparticle comminution could be occurring. The top size of the crusher feed must be ascertained to pass the feed aperture of the crusher. When fixed size distribution models are used, the top size of the feed must meet a minimum size in order to avoid anomalous results. Both Whiten and Gyradisc models must be modified for ores other than haematite. However, the accuracy of the Nordberg Gyratory model was questioned, as simulation of the primary comminution units was inaccurate.

The preferred model for crushing is one in which breakage and classification are modelled in turn for a number of breakage events in the crusher chamber, like Whiten's model. Such a model is suitable for crushers in which the two mechanisms of crushing occurring are tensile stress fracture and compressive stress fracture.

Values of K, the proportion of fines produced during breakage events, which depends on the closed side setting, should be experimentally determined, to ensure accuracy of simulation.

For the gyradisc crusher two distinct output size distributions occurred, indicating that two different mechanisms of interparticle comminution are taking place. It is hypothesised that the finer distribution results from interparticle abrasion, whereas the coarser results from fracture by compression. It was established that the CSS is indeed the predominant parameter for gyradisc crushing of a given ore, and that feed rates are not important for values within the normal operating range.

The greatest number of size classes possible should be used when simulating crushing circuits to obtain the most accurate results. The top size should be chosen to coincide with the top size of feed, thereafter size classes should be chosen with due consideration for other units in the circuit.

7.2 Screening models

Screening is best modelled using a partition curve approach to the process, as was done in this work.

The improved Microsim is equipped to deal with all decks used on the ore benficiation plant, including poly decks with non-square apertures. Using the new models various sub-plants have been accurately simulated.

The screening models developed rely on either empirical data, or on both empirical and experimental data. The screening process is sensitive to screen motion, on which very little modelling has been done up to now. Dependence of screening performance on feed properties has been suitably modelled, either by an empirical approach, like Karra, or from a consideration of mechanism, like Ferrara & Preti. The enhanced Karra model can be used where no data exist and hence is a powerful tool for ascertaining performance of new screens.

The Rose model accounts for unsteady variation of screening performance, but this unsteady variation is irrelevant in steady-state simulation.

For accuracy to be attained when simulating screening operations, it is imperative that size classes be chosen with care, as discretisation errors of steep partition curves can become large. It is recommended that size classes also be chosen to coincide with screen apertures.

The screening models are transferable to other screening applications with little or no extra data required for the simulation.

7.3 Microsim and simulation

Microsim has been used to solve a range of simulation and optimisation problems on the ore beneficiation plant. Accuracy was high on sub-plants where steady state conditions prevailed.

It is the responsibility of the user to ensure that results are within operating ranges of equipment in the flowsheet, and to obtain consistent input data.

For crushing and screening applications, the choice of a large number of size classes is important. It is recommonded that the user edit the program TYPEDEF.PAS to increase the maximum number of size classes to suit the application, observing the memory capacity of the microcomputer. If necessary, the number of grade classes may be reduced.

Optimisation should be done more than once, with various step sizes, as any premature termination of the optimisation routine will then be detected.

It is not possible to choose size classes to coincide with screen apertures if these screen apertures are variables to be optimised. This could lead to inaccurate results when a boundary and the representative size of a given class fall on different sides of the screen aperture.

The user is responsible for ensuring that model parameters which depend on optimisation variables are updated once an optimum has been found and the simulation repeated with these consistent values.

Microsim, when used skillfully, is a worthy simulator.

7.4 Closure

The improved Microsim Version 3, tailored for use on an iron-ore beneficiation plant, is a powerful tool with which process engineers and managers can assess inexpensively capabilities of the plant. It can be a valuable aid to solving many ore dressing production and design problems.

Ultimately the accuracy of Microsim depends on the quality of input data to the simulator and on the evaluative skills of the user.

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APPENDIX 1: SOFTWARE, APPARATUS AND TESTS USED

1 Software

After investigating the ore dressing simulators available, as documented in section 3, it was decided to use Modsim, available from the University of the Witwatersrand. The first version of the package was obtained in February 1986. However, the package was not entirely debugged, and two further releases were obtained before September 1986.

Since extensive work had been done on Microsim by the University of the Witwatersrand in the meantime, it was decided to use Microsim rather than Modsim, because of Microsim's expandability to hydrometallurgical stream definitions and because of its superior structure. These features have been documented in section 3.

Microsim Version 1.0 was obtained in September 1986. However, this too was not completely debugged, and was superceded by Microsim Version 2.0 in November 1986. Microsim Version 3.0, with optimisation and design capabilities, was used from January 1989.

Models added to the package for this plant were

CRUSH5
CRUSH6_7 (replaced CRUSH2_3)
SCREEN5
ROSE1
ROSE2, as described in section 4.

In order to incorporate new models into Microsim, additional program modifications have to be made to files TYPEDEF.PAS, MODEL.DAT, and MODELS.PAS. These modifications will not be given. They serve the purpose of directing the simulator's executive program to the correct model and to allocate the correct model storage space. Furthermore, the simulator's database of form-filling input screens and default parameters must be updated. This is done through compiling and executing DBASE and modifying the file MICROSIM.MOD.

Also necessary for the running of Microsim and the incorporation of

new models are DOS Version 3 (or higher) and the TURBO Pascal Version 3.0 compiler.

2 Apparatus

All software was run on an IBM-AT microcomputer with 1MB memory, 1 floppy disk drive and a 40MB hard disk. An IBM EGA graphics screen was used for the flowsheet input and a Roland DXY-980A plotter for output of flowsheets, partition curves and size distributions. The printer used was a Fujitsu DX2200 printer.

3 Tests

At the iron ore mine the following tests were performed:

- -screen analyses of material
- -chemical analyses of ore for grade

At a pilot plant in Pretoria, impact work index tests were done.

4 Data gathered

Data gathered for this work were from records at the iron ore beneficiation plant.

Information on Nordberg crushers was obtained directly from Nordberg.

Information on Microsim was obtained from the Metallurgy department of the University of the Witwatersrand.

APPENDIX 2: CORRELATIONS FOR THE KARRA MODELS

The correlations for factors A through F for the Karra model (27), and A through H for the enhanced model are calculated as follows:

Once the following have been determined:

Q=percentage oversize in feed
R=percentage half size in feed
T=theoretical undersize flow rate in tph
U=bulk density in kg/m^3

and the following parameters are known for one or two decks:

screen area in m^2, S
angle of inclination, theta
square mesh size in mm, w
length of aperture in mm, l
wire (or poly) thickness in mm, d
poly or wire deck

for one deck at a time, the effective aperture, h, in mm, and the factors A through F may be calculated from the empirical correlations of Karra and Nordberg (27,38):

$h=(w+d)\cos(\text{theta}) - d$

factor A:

if h<50,8 $A=12,1286h^{0,3162}-10,2991$
else $A=0,3388h+14,4122$

factor B:

if Q>87, $B=-0,012Q+1,6$
else $B=0,0425Q+4,275$

factor C:

if $R \leq 30$, $C=0,012R+0,7$
if $30<R<55$, $C=0,1528R^{0,564}$
if $55 \leq R<80$, $C=0,0061R^{1,37}$
if $R \geq 80$, $C=0,05R-1,5$

```
factor D:
        if top deck, D=1,0
        if second deck, D=0,9

factor E:
        let t=1,26h
        if t<1,      E=1,0
        if 1≤t≤2,    E=t
        if 2<t<4,    E=1,5+0,25t
        if 4≤t≤6,    E=2,5
        if 6<t≤10,   E=3,25-0,125t
        if 10<t<12,  E=4,5-0,25t
        if 12≤t≤16,  E=2,1-0,05t
        if 16<t<24,  E=1,5-0,125t
        if 24≤t≤32,  E=1,35-0,00625t
        if t>32,     E=1,15

factor F:
        F=U/1602

factor G (determined from poly decks used):
        if wire deck, G=1,0
        if poly deck, G=1/1,15

factor H (given in Kelly and Spottiswood (29):
        if l/w<2,    H=1,0
        if 2≤l/w<3,  H=1,1
        if 3≤l/w<6,  H=1,4
        if l/w≥6,    H=1,6
```

APPENDIX 3: PASCAL LISTINGS OF MODELS

The Pascal listings for new and modified Microsim models are given below. Models were written in accordance with the Microsim data structure as given in the Technical Reference Manual (50).

The crushing models CRUSH5 and CRUSH6_7 are contained in the Microsim library file UNIT1.PAS CRUSH6_7 replaces the general Whiten model CRUSH2_3, of which it is a modification for haematite, whereas CRUSH5 is a new model for gyradisc crushing of haematite.

The screening models ROSE1, ROSE2 and SCREEN5 were added to the Microsim library file UNIT2.PAS. SCREEN5 is an enhancement of the original Karra model, SCREEN4. ROSE1 and ROSE2 are both new models.

A3.1 Gyradisc model CRUSH5

```
{-------------------------------------------------------------------------}
{  GYRADISC MODEL - Sishen test model                                      }
{-------------------------------------------------------------------------}
OVERLAY PROCEDURE CRUSH5( var stm          : stms  ;
                          point            : tounit;
                          type_num         : UNITYPES);

   VAR
   feedpt,prodpt,der2pt                : tor4;
   feedh2o,prodh2o                     : tor6;

   g,nd,yl,y,ws,wsl,ak,an              : real ;

   i,j,k,l,m                           : integer ;

   BEGIN
     feedpt := solidselect(stm[point^.inout[2]]) ;
     prodpt := solidselect(stm[point^.inout[4]]) ;

     feedh2o := lixivselect(stm[point^.inout[2]]) ;
     prodh2o := lixivselect(stm[point^.inout[4]]) ;
     MAKESCRATCH(der2pt);

     prodh2o^.flow  := feedh2o^.flow  ;
     prodpt^.tonnes := 0.0 ;

     g := point^.param[1];

     WITH system DO
     begin
      FOR j:=1 TO ngc DO
       FOR k:=1 TO nsc DO
        FOR l:=1 TO n4c DO
         FOR m:=1 TO n5c DO
          SOLIDPUT(1,j,k,l,m,der2pt,0.0);

      FOR i:=1 TO ndc DO
       FOR j:=1 TO ngc DO
        FOR k:=1 TO nsc DO
         FOR l:=1 TO n4c DO
          FOR m:=1 TO n5c DO
           SOLIDPUT(1,j,k,l,m,der2pt,SOLIDVALUE(i,j,k,l,m,feedpt)+
                                     SOLIDVALUE(1,j,k,l,m,der2pt));
```

```
      nd := ndc -1 ;                          y1 := 1.0     ;
      FOR i := 1 to ndc DO
      BEGIN  (* for i *)
        ws := 0.0 ;
        IF i < ndc THEN ws := sqrt(size[i]*size[i+1])/g;

        IF ws >= 0.15  THEN
         begin
          an := 2.77 ;
          ak := 0.38 ;
         end
        ELSE
          begin
           an := 0.32 ;
           ak := 250.0 ;
          end;

        ws1 := POW((ws/ak),an);
        y := 1.0 ;
        IF ws1 < 10 THEN y := 1.0 - EXP(-ws1);

        FOR j := 1 TO ngc DO
         FOR k := 1 to nsc DO
          FOR l := 1 to n4c DO
           FOR m := 1 to n5c DO
            SOLIDPUT(i,j,k,l,m,prodpt,(y1-y)*SOLIDVALUE(1,j,k,l,m,der2pt));
        y1:=y;
      END; {For i}

      FOR i:=1 TO ndc DO
       FOR j:=1 TO ngc DO
        FOR k:=1 TO nsc DO
         FOR l:=1 TO n4c DO
          FOR m:=1 TO n5c DO
           prodpt^.tonnes := prodpt^.tonnes + SOLIDVALUE(i,j,k,l,m,prodpt) ;

        KILLSCRATCH(der2pt);
       END ;(* with system *)
    END; (* crush5 *)
-------------------------------------------------------------------------------
```

A3.2 Whiten model CRUSH6_7

```
{-------------------------------------------------------------------------}
{  CONE CRUSHER MODELS 6 and 7  : only for haemetite                       }
{          Standard Cone crusher model : Based on Whitens model           }
{          Short Head crusher model    : Based on Whitens model           }
{-------------------------------------------------------------------------}
OVERLAY PROCEDURE CRUSH6_7( var stm          : stms   ;
                            point            : tounit ;
                            type_num         : UNITYPES);

    VAR
    feedpt,prodpt,out2pt              : tor4;
    feedh2o,prodh2o                   : tor6;
    c,ws,ws1,w                        : REAL;
    b,b1,bii                          : REAL;
    i,j,k,l,m,ll,l1                   : integer ;


PROCEDURE WHITEN(css,kk,k1,k2,k3,n,mm : REAL);
                                       {Common calculation part}
BEGIN
 WITH system DO
 BEGIN
  FOR i:=1 TO ndc DO
  BEGIN
   c:=1;
   IF (size[i]<k2) THEN
   c:=1-POW((size[i]-k2)/(k1-k2),k3);
   IF (size[i]<k1) THEN
    c:=0.0;
   ws1:=0.0;                          ws:=size[1];
   IF (i<ndc) THEN
    ws1:=SQRT(size[i]*size[i+1]);
   IF (i>1) THEN
    ws:=SQRT(size[i-1]*size[i]);

   FOR j:=1 TO ngc DO
    FOR k:=1 TO nsc DO
     FOR l:=1 TO n4c DO
      FOR m:=1 TO n5c DO
       BEGIN
        w:=SOLIDVALUE(i,j,k,l,m,feedpt);            ll:=i-1;
        IF (ll<>0) THEN
        BEGIN
         FOR ll:=1 TO ll DO
         BEGIN
          b1:=(1-kk)*POW(ws1/size[ll],n)+kk*POW(ws1/size[ll],mm);
          b:=(1-kk)*POW(ws/size[ll],n)+kk*POW(ws/size[ll],mm)-b1;
          w:=w+b*SOLIDVALUE(ll,j,k,l,m,out2pt);
         END; {For l}
        END; {If ll}
        bii:=1-(1-kk)*POW(ws1/size[i],n)-kk*POW(ws1/size[i],mm);
        w:=w/(1-bii*c);                  SOLIDPUT(i,j,k,l,m,out2pt,w*c);
        SOLIDPUT(i,j,k,l,m,prodpt,w*(1-c));
        prodpt^.tonnes := prodpt^.tonnes+SOLIDVALUE(i,j,k,l,m,prodpt) ;
   END; {j,k,l,m}
  END; {For I}
 END; {with system}
END; {Calculate procedure}
{-------------------------------------------------------------------------}
VAR
  css,kk,k1,k2,k3,n,mm            : REAL;


BEGIN
 feedpt := solidselect(stm[point^.inout[2]]) ;
 prodpt := solidselect(stm[point^.inout[4]]) ;
 feedh2o := lixivselect(stm[point^.inout[2]]) ;
 prodh2o := lixivselect(stm[point^.inout[4]]) ;
```

```
 MAKESCRATCH(out2pt);

 prodh2o^.flow  := feedh2o^.flow  ;
 prodpt^.tonnes := 0.0 ;

 css:=point^.param[1];                kk:=point^.param[2];

 CASE point^.MODEL OF
  2 : BEGIN
       k1:=0.653*css;     k2:=1.21*css;     k3:=2.0;
       n:=2.0;    mm:=0.535;
      END; {Standard Symons cone crusher for haemetite}
  3 : BEGIN
       k1:=0.944*css;     k2:=1.722*css+0.004826;        k3:=3.0;
       n:=2.000;          mm:=0.535;
      END; {Short head cone crusher for haemetite}
 END;
 WHITEN(css,kk,k1,k2,k3,n,mm);
 KILLSCRATCH(out2pt);
END; {Procedure}
```

A3.3 Single deck Rose efficiency model ROSE1

```
{-------------------------------------------------------------------------}
{ SINGLE DECK ROSE MODEL                                                  }
{-------------------------------------------------------------------------}
OVERLAY PROCEDURE ROSE1 ( var stm          : stms    ;
                            point          : tounit ;
                            type_num       : UNITYPES);
VAR
 feedpt,out1pt,out2pt              : tor4;
 feedh2o,out1h2o,out2h2o           : tor6;
 eff,value,value2,d50,x,pof        : real ;
 i,j,k,l,m                         : integer ;

BEGIN
 feedpt := solidselect(stm[point^.inout[2]]) ;
 out1pt := solidselect(stm[point^.inout[4]]) ;
 out2pt := solidselect(stm[point^.inout[5]]) ;
 feedh2o := lixivselect(stm[point^.inout[2]]) ;
 out1h2o := lixivselect(stm[point^.inout[4]]) ;
 out2h2o := lixivselect(stm[point^.inout[5]]) ;
 out1pt^.tonnes := 0.0 ;
 out2pt^.tonnes := 0.0 ;
 eff            := point^.param[2];
 d50            :=eff*point^.param[1];

 WITH system DO
 BEGIN
  FOR i := 1 to ndc DO
    BEGIN
     x:=POW(size[i]/d50,5.846);
     IF (x<60) THEN pof:=1-EXP(-0.693*x)
     ELSE pof:=1;
     IF pof>1 THEN pof:=1
     ELSE IF pof<0 THEN pof:=0;
   FOR j := 1 TO ngc DO
    FOR k := 1 to nsc DO
     FOR l := 1 to n4c DO
      FOR m := 1 to n5c DO
      BEGIN
       value := 0.0 ;
       IF size[i] <= point^.param[1] THEN
        value := (1-pof)* solidvalue(i,j,k,l,m,feedpt);
       value2 := solidvalue(i,j,k,l,m,feedpt) - value;

       SOLIDPUT(i,j,k,l,m,out1pt,value);
       SOLIDPUT(i,j,k,l,m,out2pt,value2);

       out1pt^.tonnes := out1pt^.tonnes + value ;

       out2pt^.tonnes := out2pt^.tonnes + value2;
       END;
      END; (* for *)
 END; (* with system *)
 out1h2o^.flow := 0.95*feedh2o^.flow;
 out2h2o^.flow := 0.05*feedh2o^.flow;
END; (* rose1 *)
```

A3.4 Double deck Rose efficiency model ROSE2

```
{-------------------------------------------------------------------------}
{ DOUBLE DECK ROSE MODEL                                                  }
{-------------------------------------------------------------------------}
OVERLAY PROCEDURE ROSE2 ( var stm       : stms   ;
                          point         : tounit ;
                          type_num      : UNITYPES);

    VAR
    feedpt,outlpt,out2pt,out3pt       : tor4;
    feedh2o,outlh2o,out2h2o,out3h2o   : tor6;

    eff1,eff2,d501,d502,x1,x2,pof1,pof2  : real ;
    value,value1,value2 ,value3          : real ;

    i,j,k,l,m .                          : integer ;


    BEGIN

      feedpt := solidselect(stm[point^.inout[2]]) ;
      outlpt := solidselect(stm[point^.inout[4]]) ;
      out2pt := solidselect(stm[point^.inout[5]]) ;
      out3pt := solidselect(stm[point^.inout[6]]) ;

      feedh2o := lixivselect(stm[point^.inout[2]]) ;
      outlh2o := lixivselect(stm[point^.inout[4]]) ;
      out2h2o := lixivselect(stm[point^.inout[5]]) ;
      out3h2o := lixivselect(stm[point^.inout[6]]) ;

      outlpt^.tonnes := 0.0 ;
      out2pt^.tonnes := 0.0 ;
      out3pt^.tonnes := 0.0 ;

      eff1            := point^.param[2];
      eff2            := point^.param[4];
                      d501:=eff1*point^.param[1];
                      d502:=eff2*point^.param[3];

      WITH system DO begin

        FOR i := 1 to ndc DO
        BEGIN
         x1:=POW(size[i]/d501,5.846);
         x2:=POW(size[i]/d502,5.846);
        IF (x1<60) THEN pof1:=1-EXP(-0.693*x1)
        ELSE pof1:=1;
        IF pof1>1 THEN pof1:=1
        ELSE IF pof1<0 THEN pof1:=0;
        IF (x2<60) THEN pof2:=1-EXP(-0.693*x2)
        ELSE pof2:=1;
        IF pof2>1 THEN pof2:=1
        ELSE IF pof2<0 THEN pof2:=0;
        FOR j := 1 TO ngc DO
        FOR k := 1 to nsc DO
        FOR l := 1 to n4c DO
        FOR m := 1 to n5c DO
         BEGIN
          value := solidvalue(i,j,k,l,m,feedpt) ;
          IF size[i] < point^.param[1] THEN
                       value2 := (pof1) * value  ;
          IF size[i] >= point^.param[1] THEN
                       value2 := value;
          IF size[i] < point^.param[3] THEN
                       value3 := (pof2)*(value-value2);
          IF size[i] >= point^.param[3] THEN
                       value3 := (value-value2);

         value1 := value-value2-value3;
```

```
        solidput(i,j,k,l,m,out1pt,value1);
        solidput(i,j,k,l,m,out2pt,value2);
        solidput(i,j,k,l,m,out3pt,value3);

        out1pt^.tonnes := out1pt^.tonnes + value1;
        out2pt^.tonnes := out2pt^.tonnes + value2;
        out3pt^.tonnes := out3pt^.tonnes + value3;
                                  END;
        END; (* for *)


      out1h2o^.flow := feedh2o^.flow * 0.9 ;
      out2h2o^.flow := feedh2o^.flow * 0.05;
      out3h2o^.flow := feedh2o^.flow * 0.05;
    END; (* with system *)
  END; (* rose2 *)
```

A3.5 Enhanced Karra Model SCREEN5

```
{-------------------------------------------------------------------------}
{ SCREEN MODEL 5                                                          }
{         Enhanced  Karra screen model for single or double screens       }
{-------------------------------------------------------------------------}
OVERLAY PROCEDURE SCREEN5(VAR stm : STMS;
                             point : TOUNIT;
                         type_num : UNITYPES);


 PROCEDURE PARTICLE_SIZE(stream_ptr : TOR4;
                     VAR cumulative : SIZES);

 VAR
  cumulat : REAL;
  i       : INTEGER;

 BEGIN
  cumulat:=0;
  FOR i:=1 TO system.NDC DO
  BEGIN
   cumulat:=cumulat+SIGNDC(i,stream_ptr);
   cumulative[i]:=100-cumulat;
  END;
 END;
 {-------------------------------------------------------------------------}
 FUNCTION INTERPOLATE( x,y : SIZES;
                         n : INTEGER;
                        xx : REAL) : REAL;

 VAR
  c                        : ARRAY[sizrange,1..3] OF REAL;
  i,n0,k                   : INTEGER;
  rm3,t1,rm2,rm1,rm4,t2,b  : REAL;

 BEGIN
  rm3:=(y[2]-y[1])/(x[2]-x[1]);          t1:=rm3-(y[2]-y[3])/(x[2]-x[3]);
  rm2:=rm3+t1;                           rm1:=rm2+t1;
  n0:=n-2;

  FOR i:=1 TO N DO BEGIN
   IF (i>n0) THEN
    rm4:=rm3-rm2+rm3
   ELSE
    rm4:=(y[I+2]-y[i+1])/(x[I+2]-x[I+1]);
   t1:=ABS(rm4-rm3);                    t2:=ABS(rm2-rm1);
   b:=t1+t2;
   IF (b<>0) THEN
    c[i,1]:=(t1*rm2+t2*rm3)/B
   ELSE
    c[i,1]:=0.5*(rm2+rm3);
   rm1:=rm2;      rm2:=rm3;          rm3:=rm4
  END;

  n0:=n-1;

  FOR i:=1 TO n0 DO BEGIN
   t1:=1/(x[I+1]-x[i]);                 t2:=(y[i+1]-y[i])*t1;
   b:=(c[i,1]+c[i+1,1]-t2-t2)*t1;       c[i,3]:=b*t1;
   c[i,2]:=-b+(t2-c[i,1])*t1
  END;

  FOR i:=1 TO n-1 DO
   IF ((xx>=x[i]) AND (xx<x[I+1])) THEN k:=i;
  xx:=xx-x[k];
  interpolate:=c[k,3]*xx*xx*xx+c[k,2]*xx*xx+c[k,1]*xx+y[k]
 END;
```

```
{-------------------------------------------------------------------------------}
 FUNCTION  PERCENTAGE_PASSING(cumulative  :  SIZES;          {Find  %  passing psize}
                              psize       :  REAL) : REAL;   {psize  in  microns    }
 VAR
  x,y          : SIZES;
  i            : INTEGER;
  dummy        : REAL;

 BEGIN
  psize:=psize/1E6;                    {Convert to metres}
  WITH system DO
  BEGIN
   FOR i:=1 TO ndc DO
   BEGIN
    x[i]:=size_class[ndc-i+1];
    y[i]:=cumulative[ndc-i+1];
   END;
   IF psize>size_class[1] THEN
   BEGIN
    dummy:=psize/size_class[1]*cumulative[1];
    IF dummy>100 THEN dummy:=100;
   END
   ELSE
    dummy:=INTERPOLATE(x,y,ndc,psize);
  END;
  percentage_passing:=dummy;
 END;
  {-------------------------------------------------------------------------}
  PROCEDURE MODCALC_ONE_DECK(feedpt,ofpt,ufpt : TOR4;
                             lw,ht,area,poly : REAL;              {Ht in mm}
                                       deck  : INTEGER;
                                       water : REAL);

  VAR
   i,j,k,l,m                                    : INTEGER;
   a,b,c,d,e,f,kk,xn,p,q,r,t,g,h                : REAL;
   undersize_theory,svm,sga,u,pof,d50,x         : REAL;
   cumulative                                   : SIZES;

  BEGIN
   PARTICLE_SIZE(feedpt,cumulative);                  {Get cumulative in feed}
   q:=100-PERCENTAGE_PASSING(cumulative,ht*1000);     {% oversize in feed    }
   r:=PERCENTAGE_PASSING(cumulative,ht*500);          {% half size in feed   }
   xn:=PERCENTAGE_PASSING(cumulative,1250*ht)-
       PERCENTAGE_PASSING(cumulative,750*ht);         {% near size in feed   }
   undersize_theory:=(1-q/100)*feedpt^.TONNES*3.6;    {Theoretical underflow TPH}
   p:=ht;
   t:=1.26*ht;
                    {Get constants A,B,C,D,E,F,G,H}
   IF (p>=50.8) THEN a:=14.4122+0.3388*p
   ELSE a:=12.1286*POW(p,0.3162)-10.2991;

   IF (q>87) THEN b:=4.275+0.0425*q
   ELSE b:=1.6-0.012*q;

   IF (r>=80) THEN c:=0.05*r-1.5
   ELSE
    IF ((r<80) AND (r>=55)) THEN c:=0.0061*POW(r,1.37)
    ELSE
     IF ((r<55) AND (r>30)) THEN c:=0.1528*POW(r,0.564)
     ELSE c:=0.012*r+0.7;

   d:=1.1-0.1*deck;
   {g = polydeck factor for reduced area}
   {h = factor for nonsquare apertures}
   IF poly=1.0 THEN g:=1./1.15
   ELSE g:=1.0;
   IF lw<2.0 THEN h:=1.0
   ELSE
     IF lw<3.0 THEN h:=1.1
```

```
    ELSE
      IF lw<6 THEN h:=1.4
      ELSE h:=1.6;
  IF (water>0) THEN      {Wet screening}
  BEGIN
   IF (t>32) THEN e:=1.15
   ELSE
    IF ((t<=32) AND (t>=24)) THEN e:=1.35-0.00625*t
    ELSE
     IF ((t<24) AND (t>16)) THEN e:=1.5-0.0125*t
     ELSE
      IF ((t<=16) AND (t>=12)) THEN e:=2.1-0.05*t
      ELSE
       IF ((t<12) AND (t>10)) THEN e:=4.5-0.25*t
       ELSE
        IF ((t<=10) AND (t>6)) THEN e:=3.25-0.125*t
        ELSE
         IF ((t<=6) AND (t>=4)) THEN e:=2.5
         ELSE
          IF ((t<4) AND (t>2)) THEN e:=1.5+0.25*t
          ELSE
           IF ((t<=2) AND (t<=1)) THEN e:=t
           ELSE
            e:=1.0;

   sga:=Ore_Density(feedpt);
   if sga > 0.0 then svm:=1/(1000*sga)
                else svm:=0;
   u:=sga*0.6*1000;
   f:=u/1602;
  END
  ELSE
  BEGIN                                                {Dry screening}
   e:=1;                f:=1;
  END;

  kk:=undersize_theory/area/(a*b*c*d*e*f*g*h);

  d50:=0.975*ht*POW(kk,-0.148)*POW((1-xn/100),0.511);

  d50:=d50*1e-03;                                      {D50 in meters}

  ufpt^.TONNES:=0.0;          ofpt^.TONNES:=0.0;
  WITH system DO
  BEGIN
   FOR i:=1 TO ndc DO
   BEGIN
    x:=POW(size[i]/d50,5.846);
    IF (x<60) THEN pof:=1-EXP(-0.693*x)
    ELSE pof:=1;
    IF pof>1 THEN pof:=1
    ELSE IF pof<0 THEN pof:=0;
    FOR j:=1 TO ngc DO
     FOR k:=1 TO nsc DO
      FOR l:=1 TO n4c DO
       FOR m:=1 TO n5c DO
       BEGIN
        SOLIDPUT(i,j,k,l,m,ofpt,pof*SOLIDVALUE(i,j,k,l,m,feedpt));
        SOLIDPUT(i,j,k,l,m,ufpt,SOLIDVALUE(i,j,k,l,m,feedpt)
                               -SOLIDVALUE(i,j,k,l,m,ofpt));
        ufpt^.TONNES:=ufpt^.TONNES+SOLIDVALUE(i,j,k,l,m,ufpt);
        ofpt^.TONNES:=ofpt^.TONNES+SOLIDVALUE(i,j,k,l,m,ofpt);
       END;
    END;
   END;
  END;
  {-------------------------------------------------------------------------}
VAR
 feedpt,out1pt,out2pt,out3pt,dummyfeedpt : TOR4;
 feedh2o,out1h2o,out2h2o,out3h2o         : TOR6;
```

```
 i,j,k,l,m                                  : INTEGER;
 area,ht,theta,water,lw,poly                : REAL;
 deck                                       : INTEGER;

BEGIN
 feedpt := solidselect(stm[point^.inout[2]]) ;
 outlpt := solidselect(stm[point^.inout[4]]) ;
 out2pt := solidselect(stm[point^.inout[5]]) ;

 IF (type_num=19) THEN
 BEGIN
  out3pt := solidselect(stm[point^.inout[6]]) ;
  out3h2o := lixivselect(stm[point^.inout[6]]) ;
 END;

 feedh2o := lixivselect(stm[point^.inout[2]]) ;
 outlh2o := lixivselect(stm[point^.inout[4]]) ;
 out2h2o := lixivselect(stm[point^.inout[5]]) ;

 MAKESCRATCH(dummyfeedpt);

 area:=point^.param[1];          theta:=point^.param[2]/180*3.1416;
 WITH point^ DO
 BEGIN
  ht:=(param[3]+param[5])*COS(theta)-param[5];
  lw:=param[4]/param[3];
  poly:=param[6];
  END;
 water:=feedh2o^.FLOW*3.6;

 MODCALC_ONE_DECK(feedpt,out2pt,dummyfeedpt,lw,ht,area,poly,1,water);

 WITH system DO
  CASE type_num OF
   15 : BEGIN
         FOR i:=1 TO ndc DO
          FOR j:=1 TO ngc DO
           FOR k:=1 TO nsc DO
            FOR l:=1 TO n4c DO
             FOR m:=1 TO n5c DO
              SOLIDPUT(i,j,k,l,m,outlpt,SOLIDVALUE(i,j,k,l,m,dummyfeedpt));
         outlpt^.TONNES:=dummyfeedpt^.TONNES;
         outlh2o^.FLOW:=0.95*feedh2o^.FLOW;
         out2h2o^.FLOW:=0.05*feedh2o^.FLOW;
        END;
   19 : BEGIN

    WITH point^ DO
    BEGIN
          ht:=(param[7]+param[9])*COS(theta)-param[9];
          lw:=param[8]/param[7];
          poly:=param[10];
          END;
         MODCALC_ONE_DECK(dummyfeedpt,out3pt,outlpt,lw,ht,area,poly,2,water);
         outlh2o^.flow := feedh2o^.flow * 0.9 ;
         out2h2o^.flow := feedh2o^.flow * 0.05;
         out3h2o^.flow := feedh2o^.flow * 0.05;
        END;
  END;

 KILLSCRATCH(dummyfeedpt);
END;
```